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High baroclinic equatorial Kelvin waves and Central Pacific Surface Warming

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High Baroclinic Equatorial Kelvin Waves and Central Pacific Surface Warming

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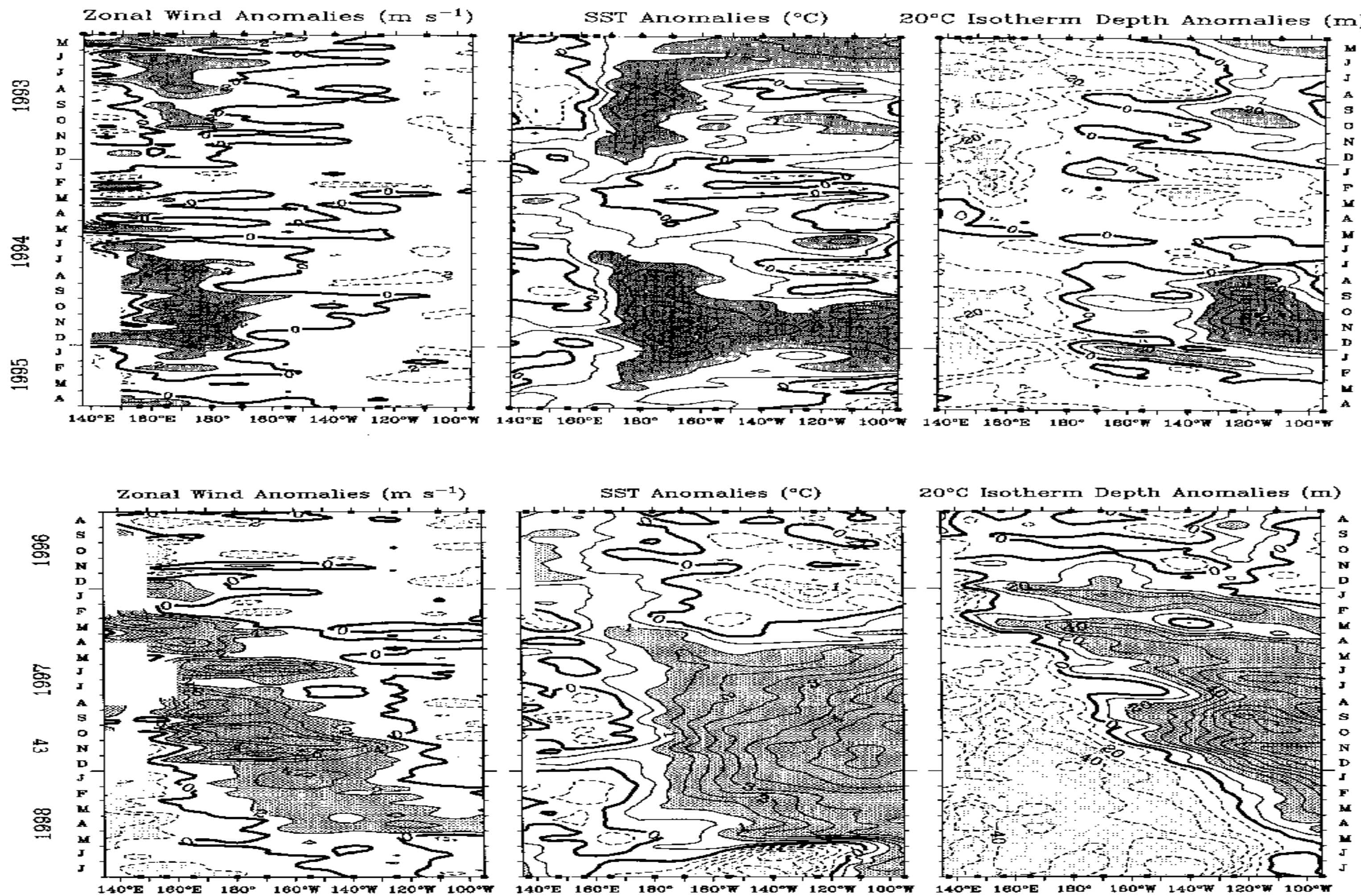
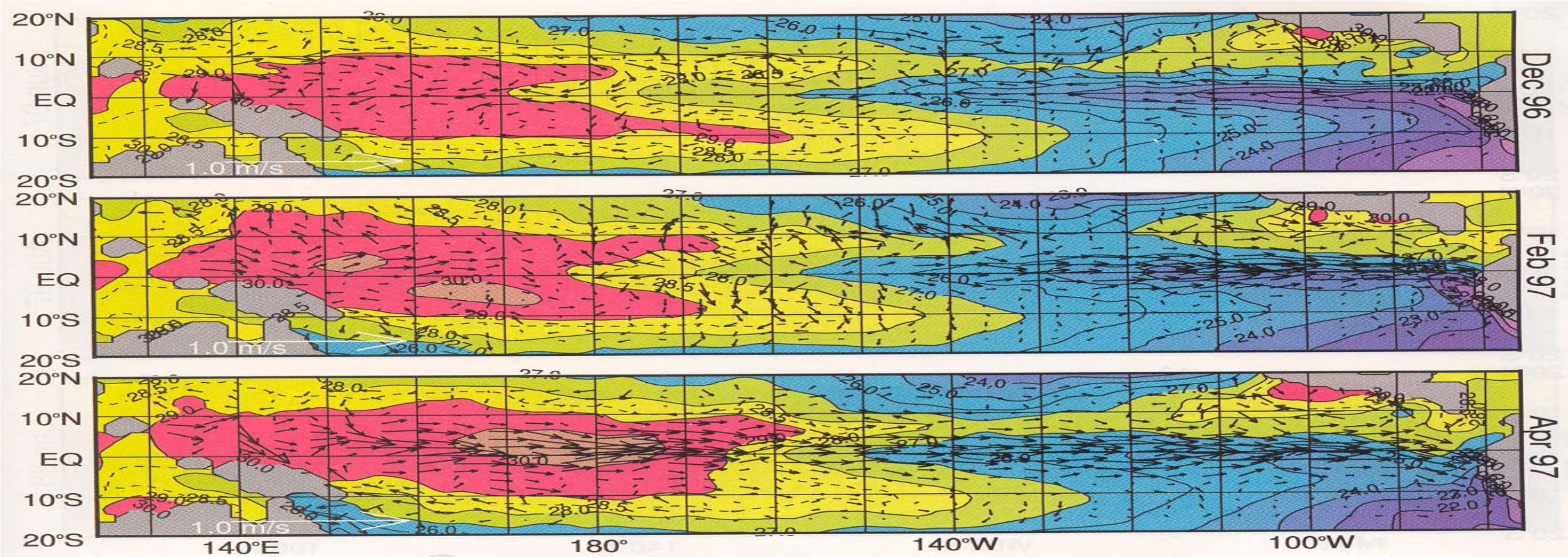
Outline

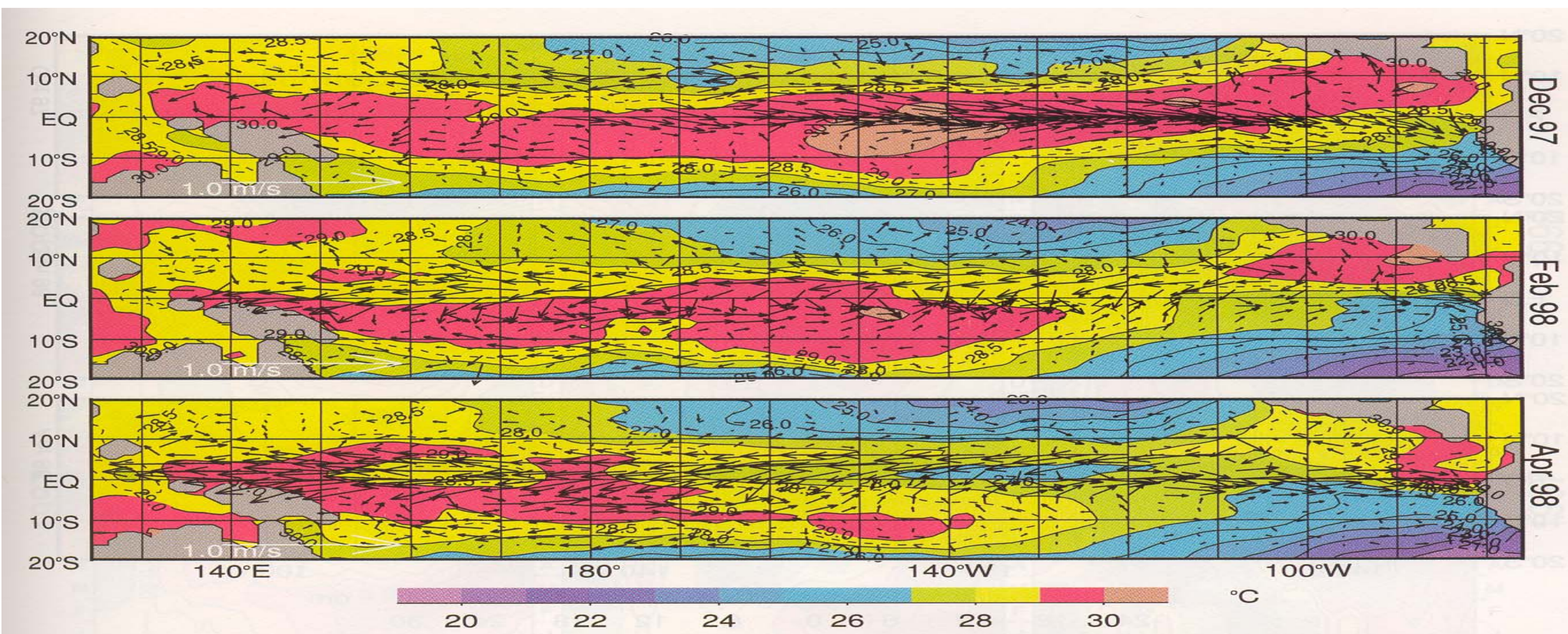
- Enhancing Counter Mode (ECM)
- Second Baroclinic Equatorial Kelvin Waves
- Two-Stage Air-Sea Interaction for the El Nino Onset

Central Pacific Warming Prior to the El Nino Onsets in 90’s

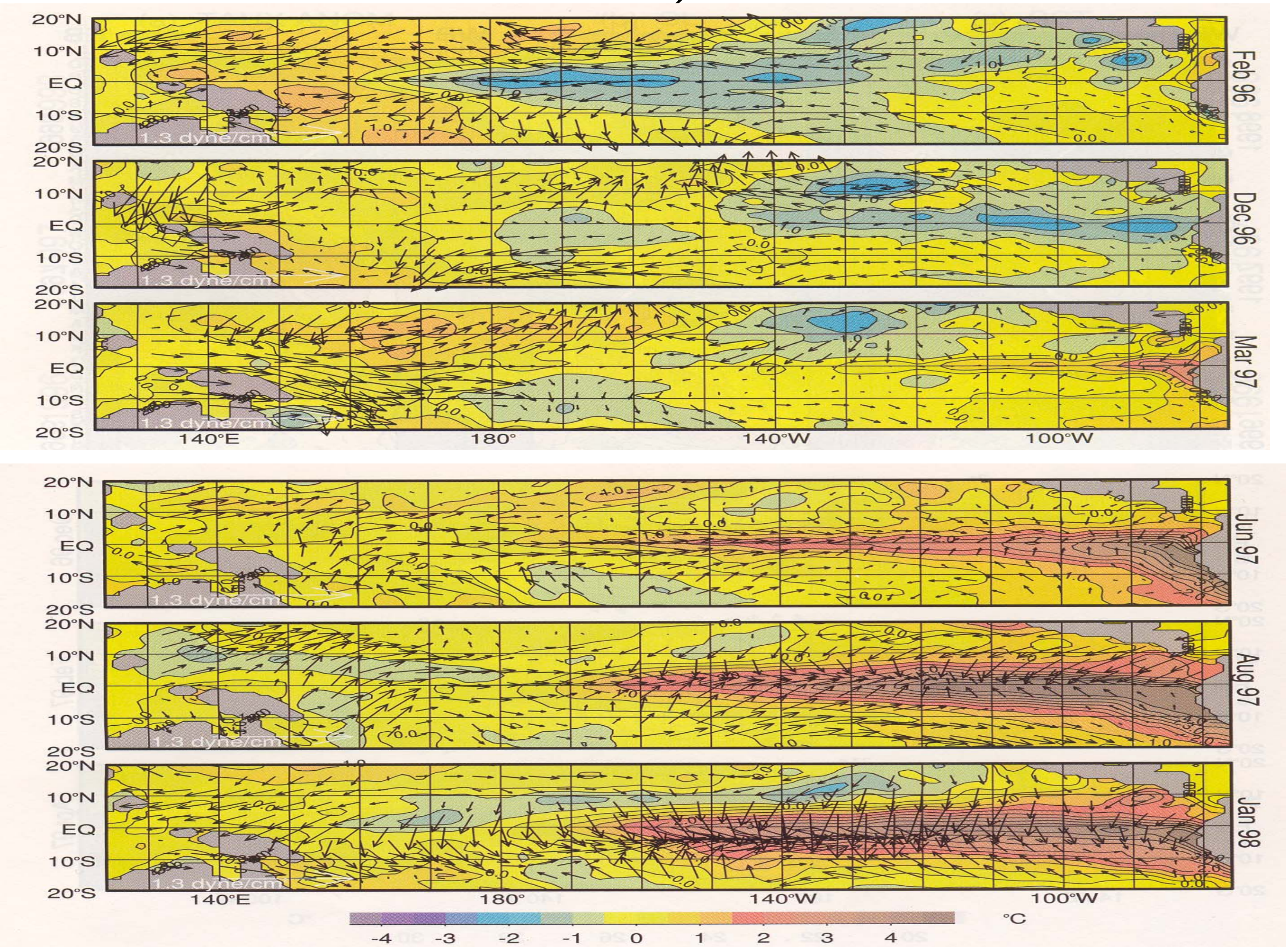


1997 El Nino – Central Pacific Warming (Picaut et al. 2002)





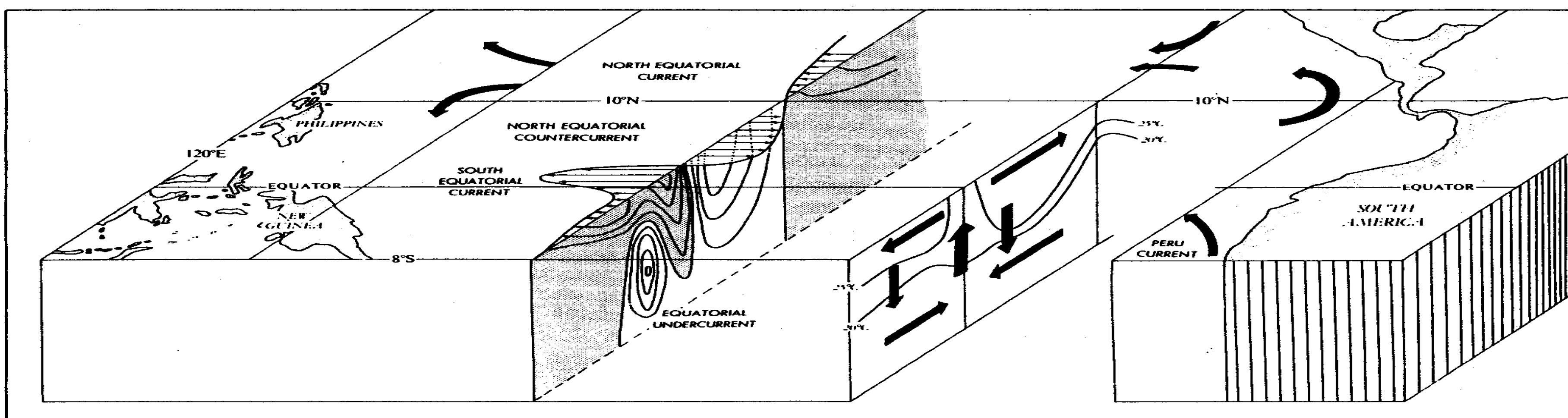
1997 El Nino – Westerly Wind Burst (Picaut et al. 2002)



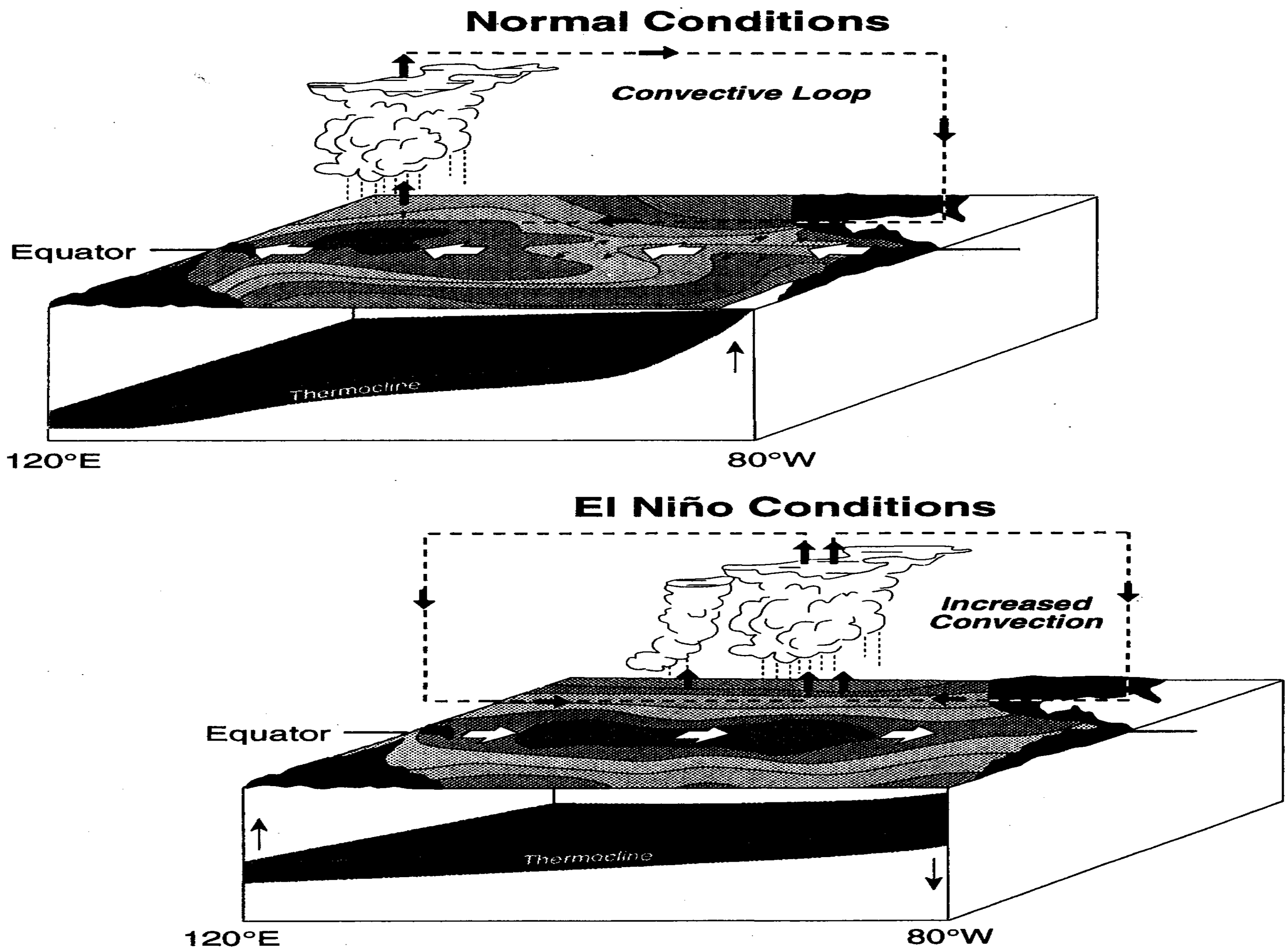
Equatorial Current System

Upper Layer:
Westward Flowing
South Equatorial Current (SEC)

Thermocline:
Eastward Flowing
Equatorial Counter Current (EUC)



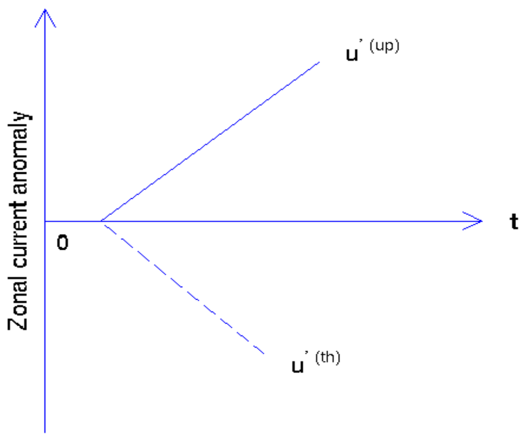
McPhaden et al. (JGR, 1998)



Mean Current System

- Upper Layer
  - SEC   (Westward)
- Thermocline
  - EUC (Eastward)
- Mean Surface Cold Advection (Mean Surface Temperature Decreasing Eastward)

Perturbation Current System Enhancing Counter Mode (ECM)



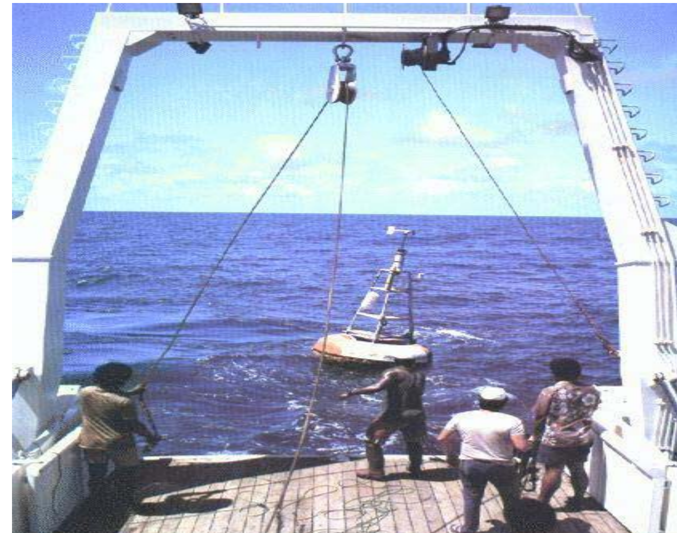
- Upper Layer Eastward Flow
- Thermocline westward Flow
- Reduction of Mean Surface Cold Advection

$$u'^{(Up)} > 0, \quad \partial u'^{(Up)} / \partial t > 0$$

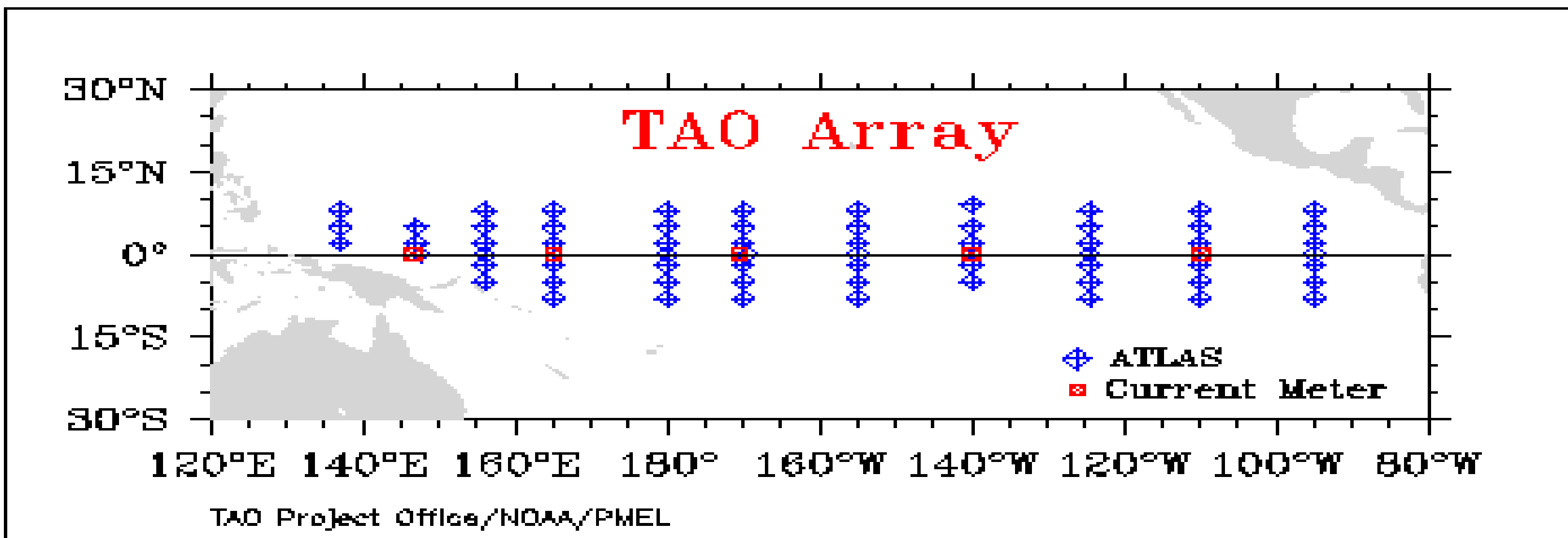
$$u'^{(Th)} < 0, \quad \partial u'^{(Th)} / \partial t < 0$$

Enhancing CM Detected from TAO Data

Servicing an ATLAS mooring of the TOGA-TAO Array. ATLAS moorings measure surface winds, air temperature, relative humidity, sea surface temperature, and subsurface temperature to depths of 500 m.



Recovering an ATLAS mooring from the French R/V LE NOROIT in the western equatorial Pacific Ocean. A total of 59 ATLAS moorings are deployed at present in the equatorial Pacific as part of the TOGA-TAO Array.

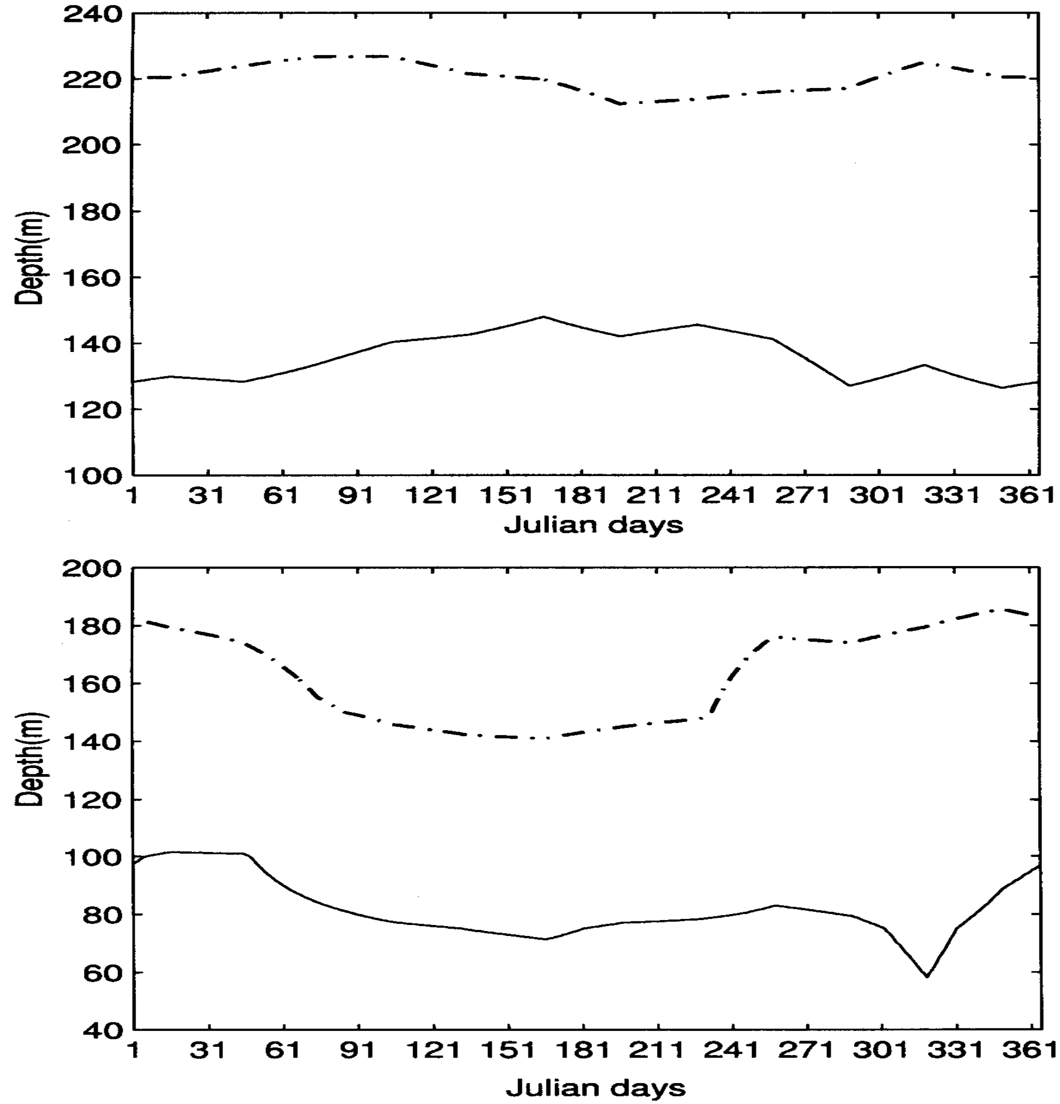


Upper Layer and Thermocline (Wyrtki and Kilonsky 1984)

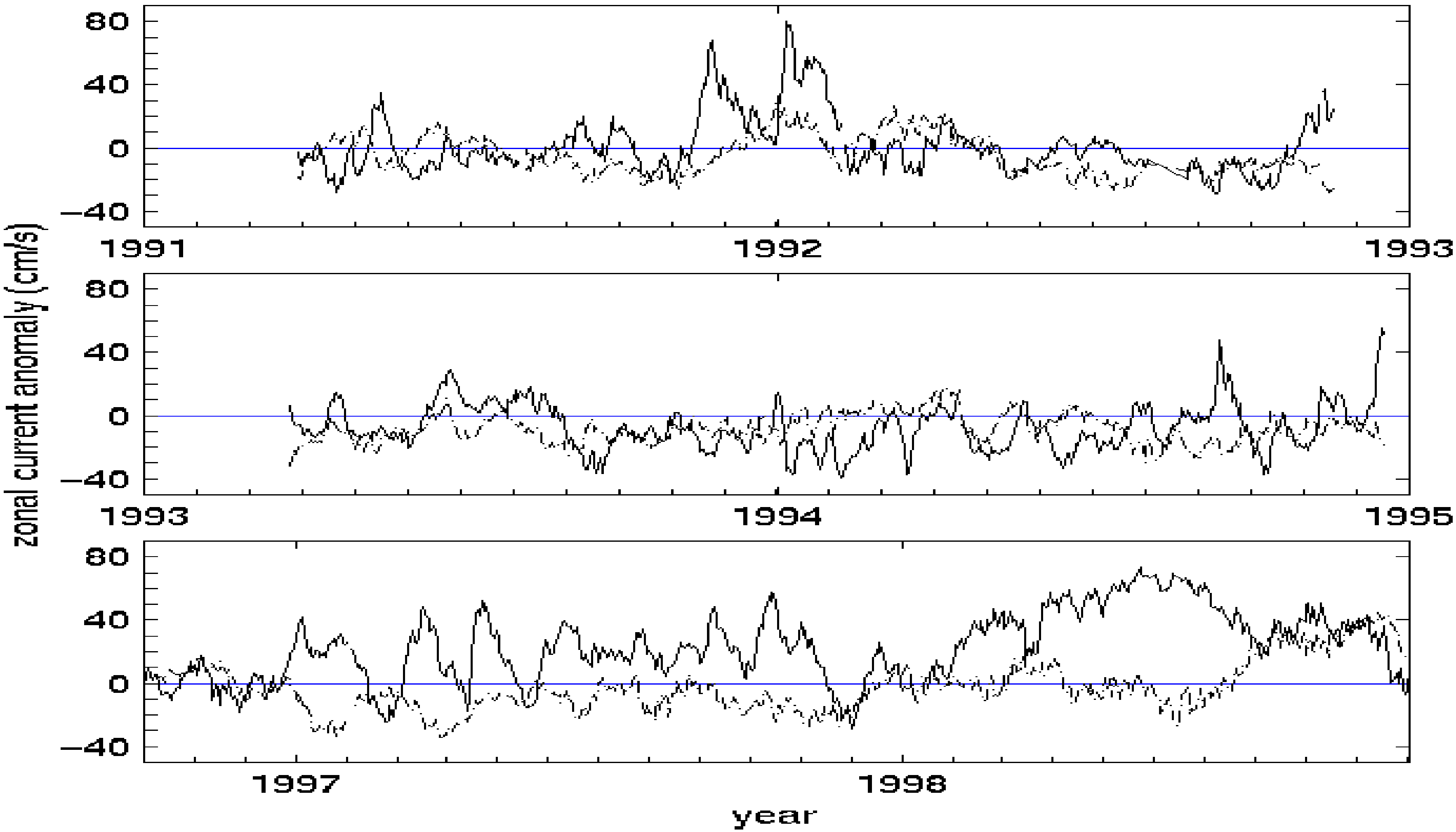
- Hawaii to Tahiti Temperature Data (1978-1980)
- Upper Layer
  - Surface to 25^{o}C depth
- Thermocline
  - 25^{o}C depth to 15^{o}C depth

(a) 165°E

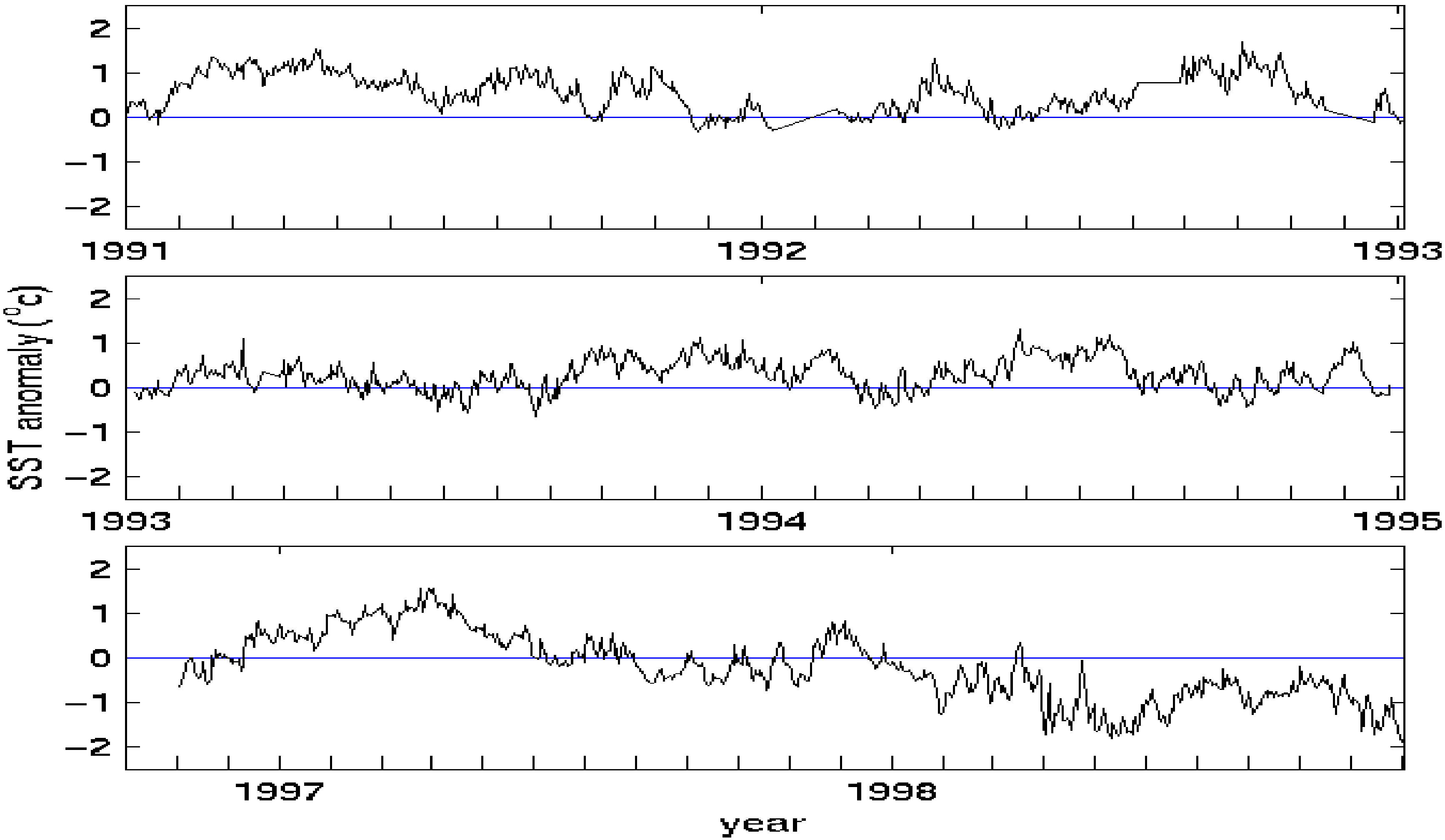
(b) 140°W



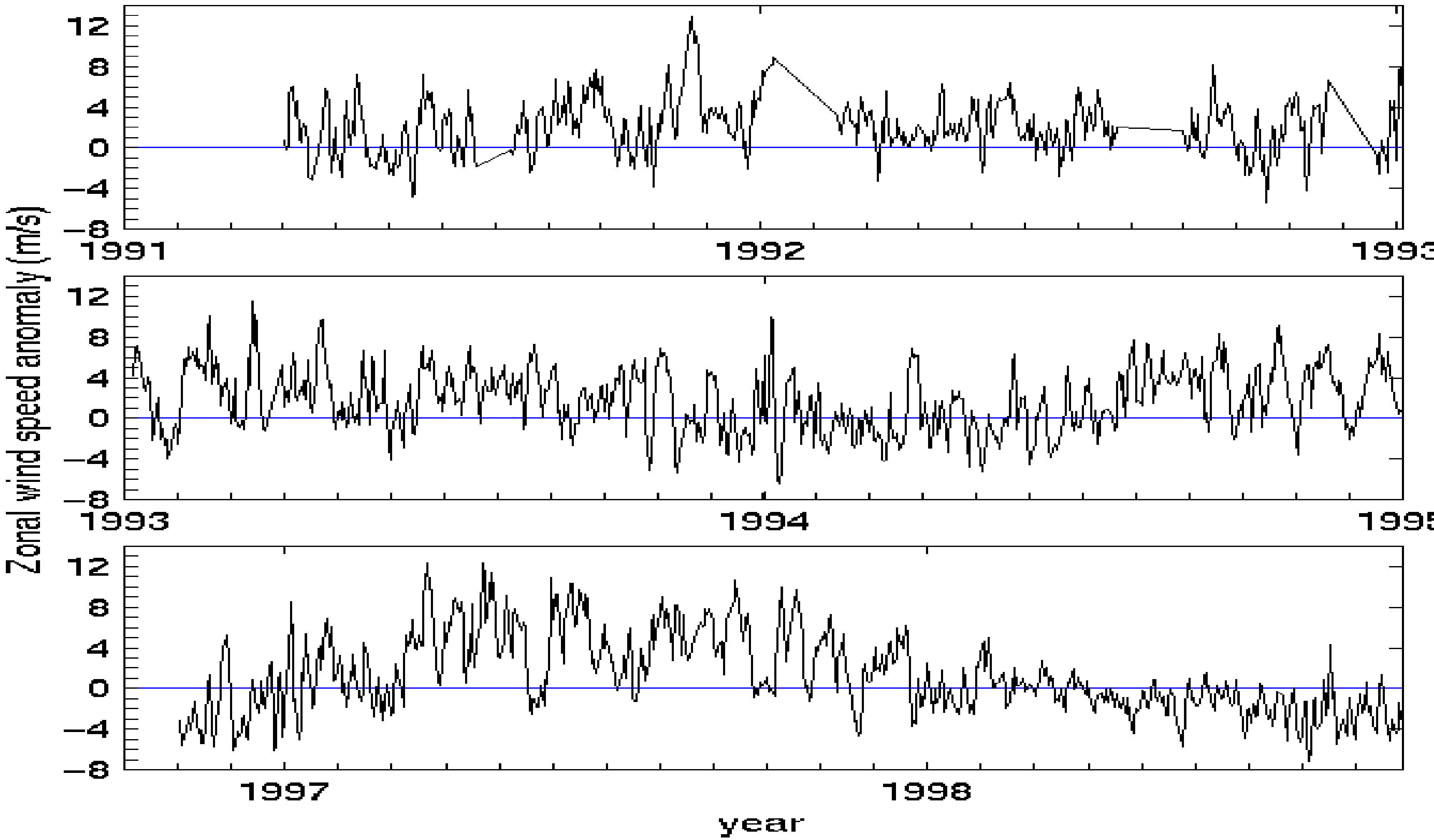
Daily Mean Depths of 25°C (Solid) and 15°C (dashed) Isotherms at (a) 165°E, and (b) 140°W along the Equator.



Enhancing CM detected from the TAO data at 165^{o}E. Here solid (dashed) curve is the upper layer (thermocline) zonal speed anomaly.



Time evolution of SST anomaly at 165^{o}E (solid). Note that SST warm anomaly appears during the ECM periods.



Time evolution of zonal wind speed anomaly (m/s) at 165°E obtained from the TAO data. Note that the west wind anomaly (> *0*) appears during the ECM periods.

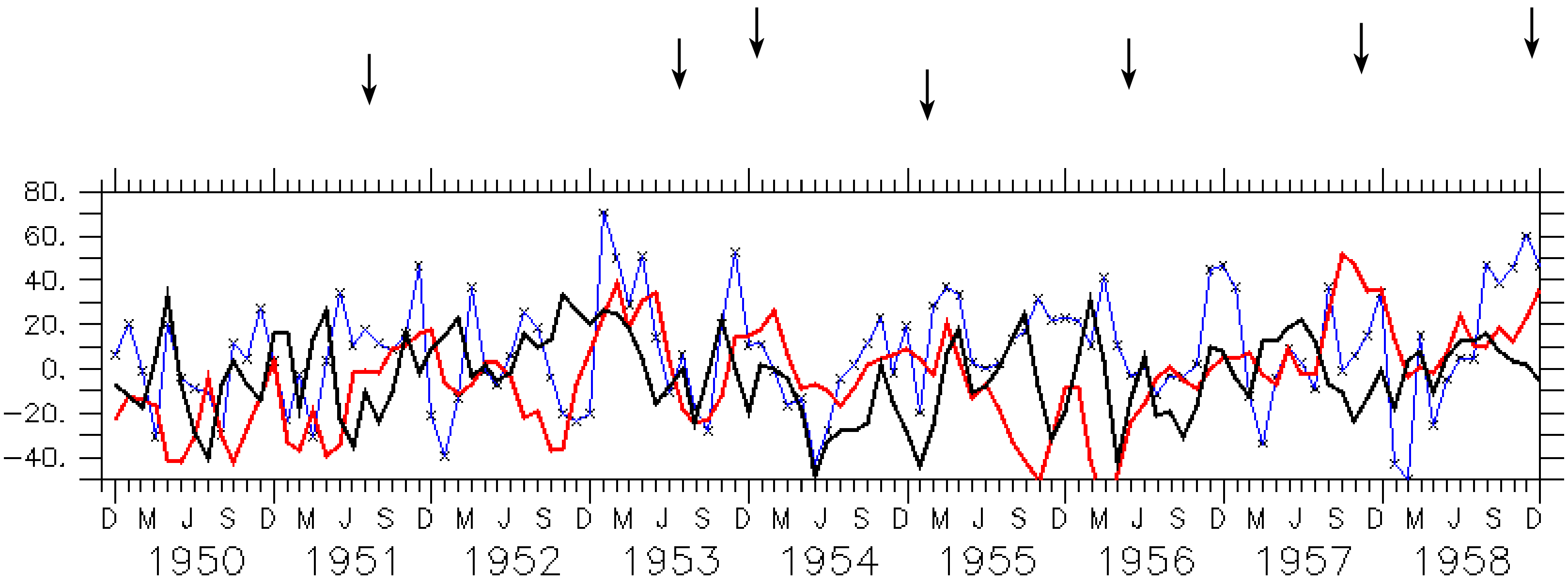
Simple Ocean Data Assimilation (SODA) System (Carton et al., 2000)

- MOM (NOAA/GFDL)
- 62^{o}S – 62^{o}N
- Data Assimilated
  - WOA-94
  - Satellite Altimetry (GEOSAT, ERS-1, T/P)
- Resolution:
  - Zonal 1^{o}
  - Meridional Varying, 0.4286^{o} near the equator

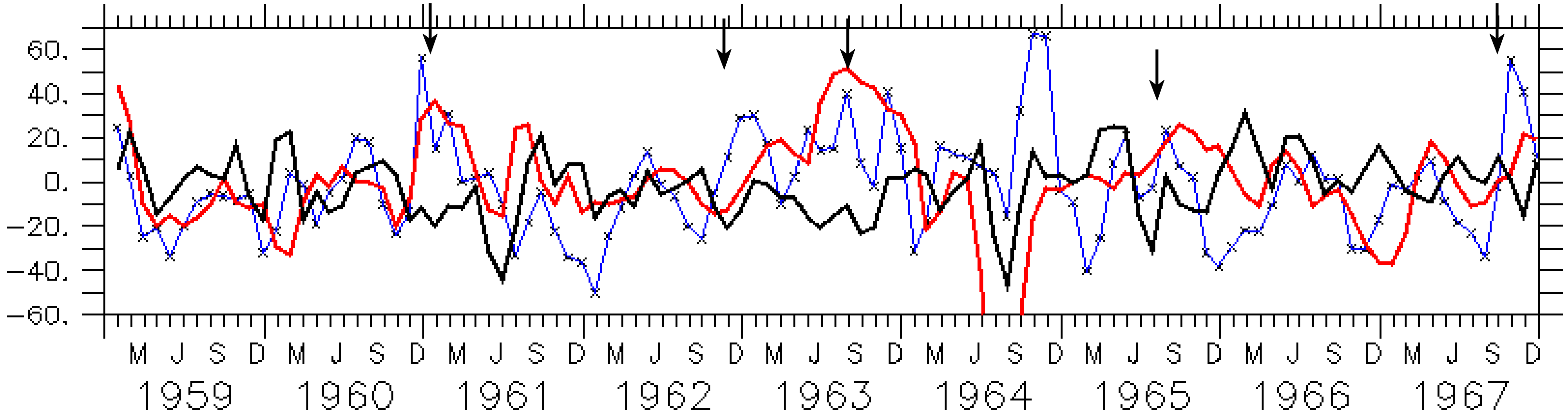
ECM Detected from SODA Data

- Monthly mean temperature and velocity data since 1950.
- SST
- Upper Layer Zonal Velocity
- Thermocline Zonal Velocity

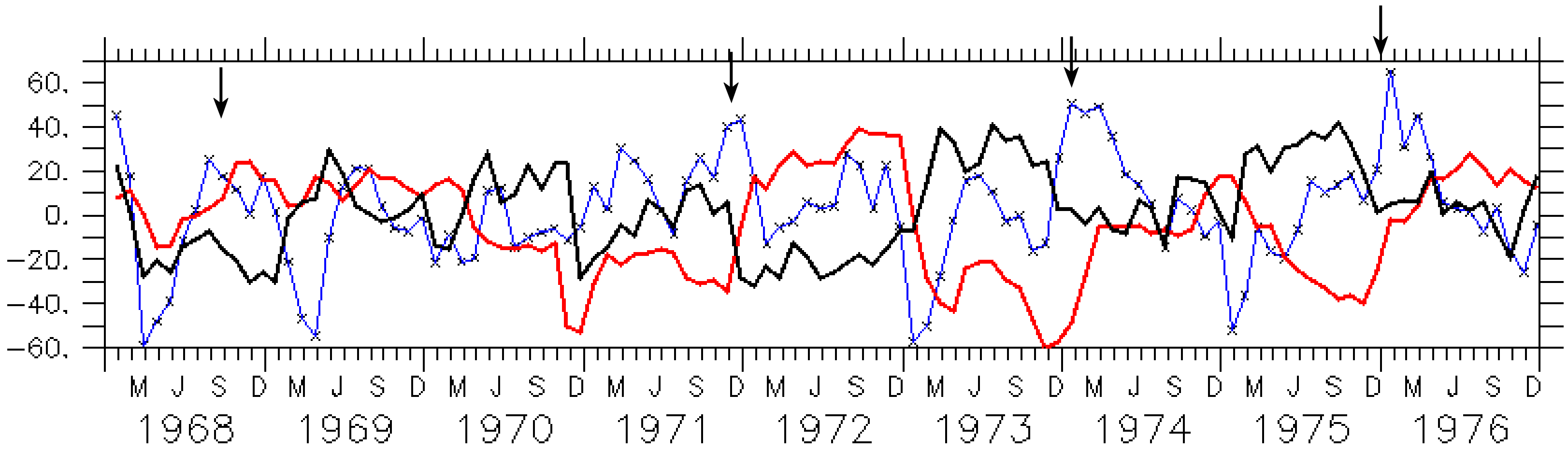
Upper Layer *u'* (cm/s, Blue)
Thermocline *u'* (cm/s, Black)
SST' (^{o}C * 12)
at 165^{o}E



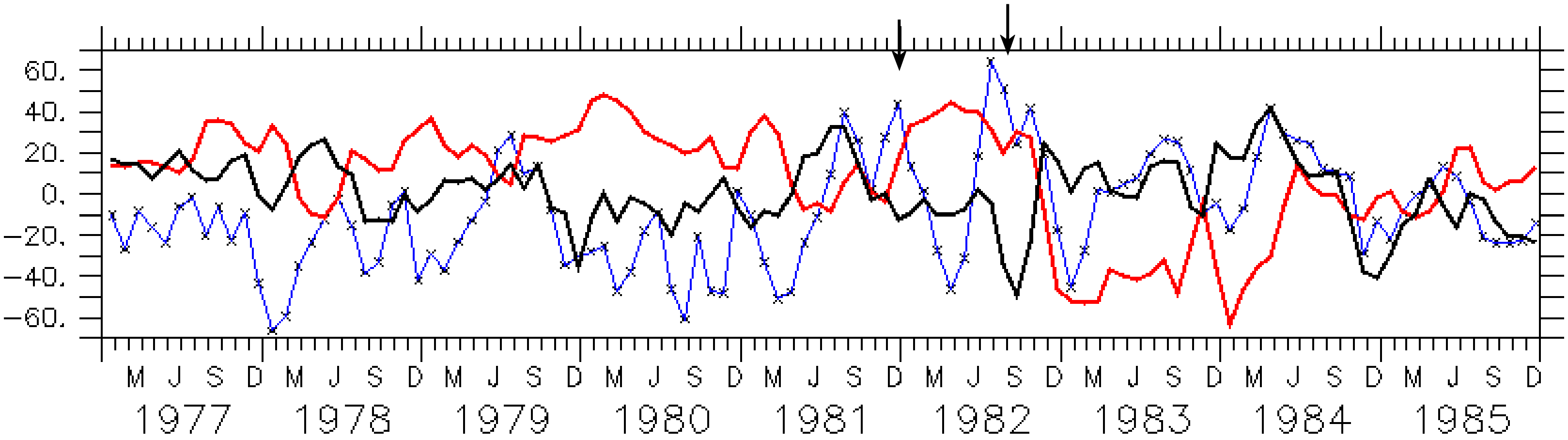
Upper Layer *u'* (cm/s, Blue)
Thermocline *u'* (cm/s, Black)
SST' (^{o}C * 12)
at 165^{o}E



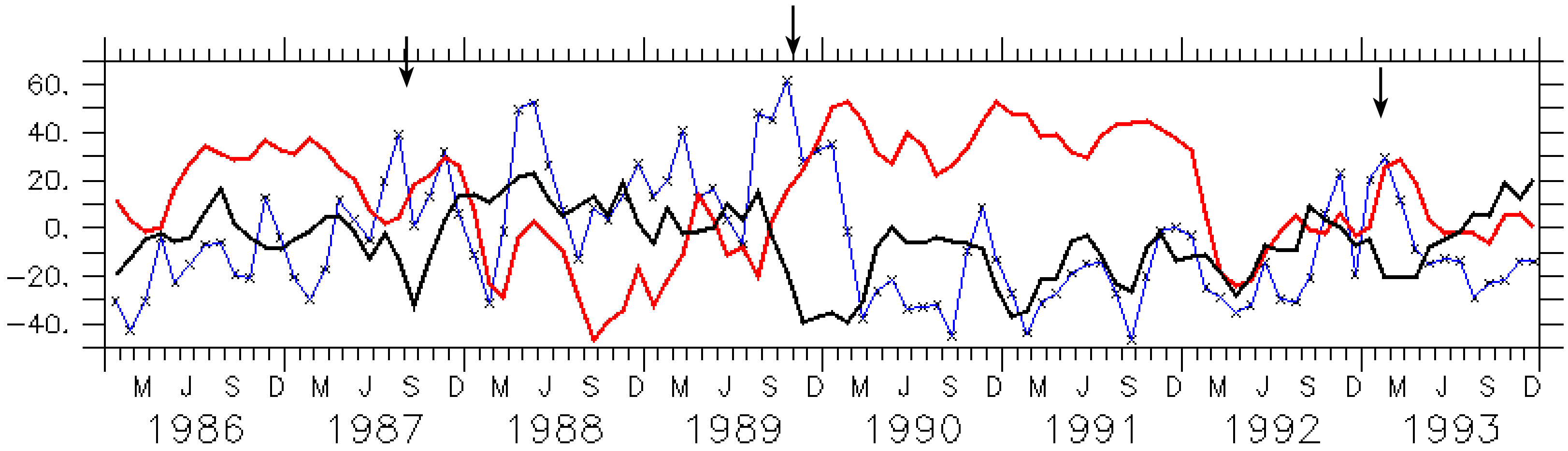
Upper Layer *u'* (cm/s, Blue)
Thermocline *u'* (cm/s, Black)
SST' (^oC * 12)
at 165^{o}E



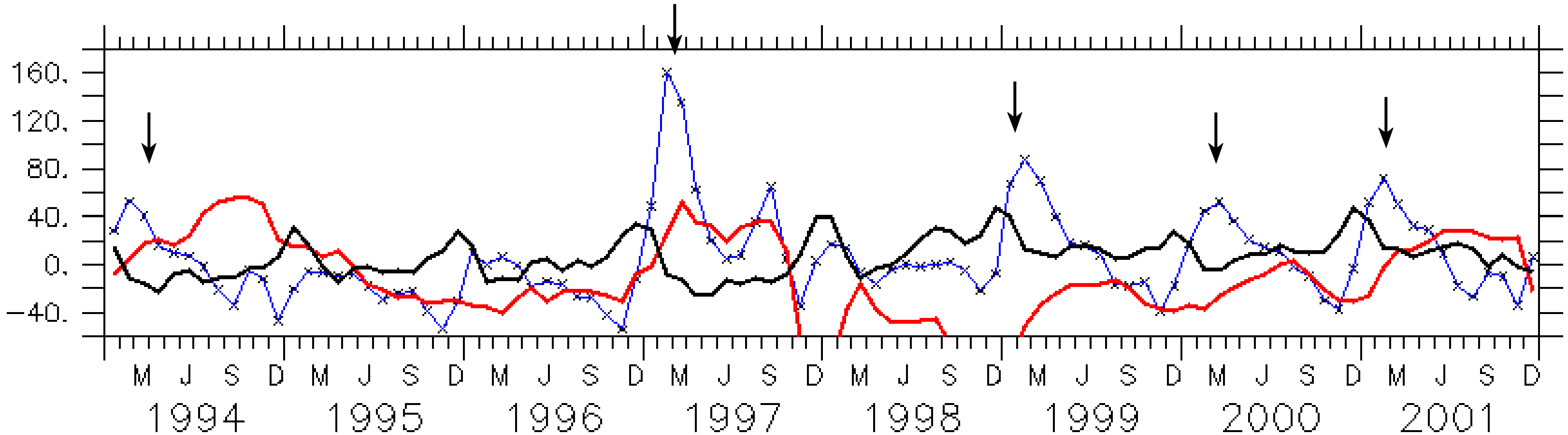
Upper Layer *u'* (cm/s, Blue)
Thermocline *u'* (cm/s, Black)
SST' (^oC * 12)
at 165^{o}E



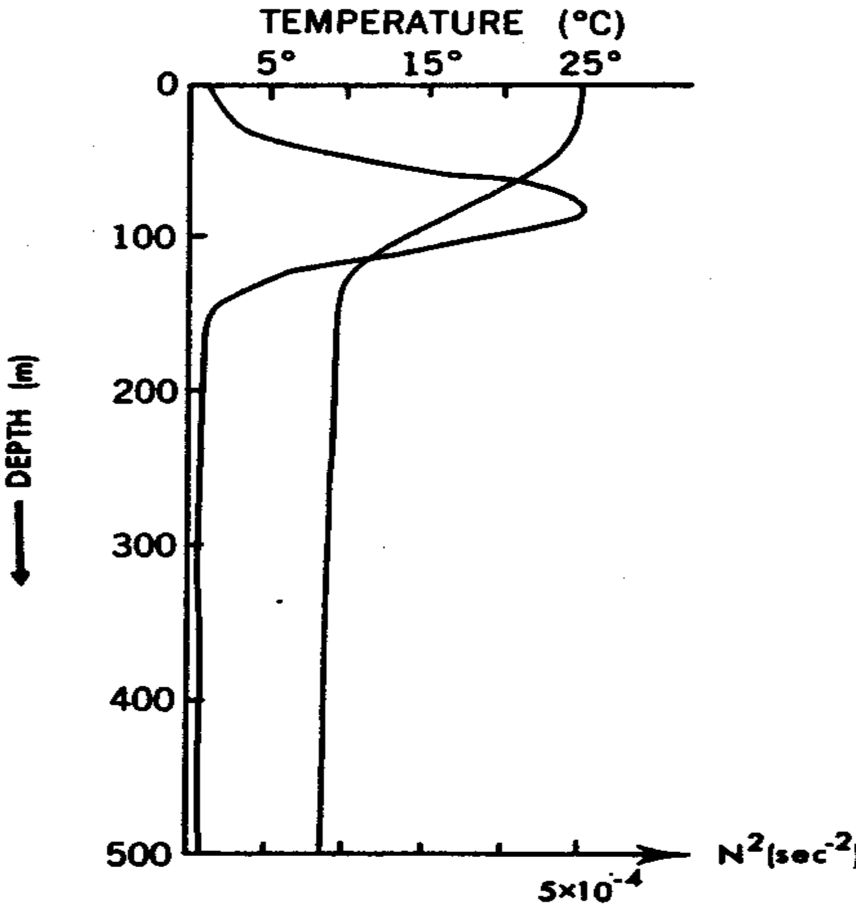
Upper Layer *u'* (cm/s, Blue)
Thermocline *u'* (cm/s, Black)
SST' (^{o}C * 12)
at 165^{o}E



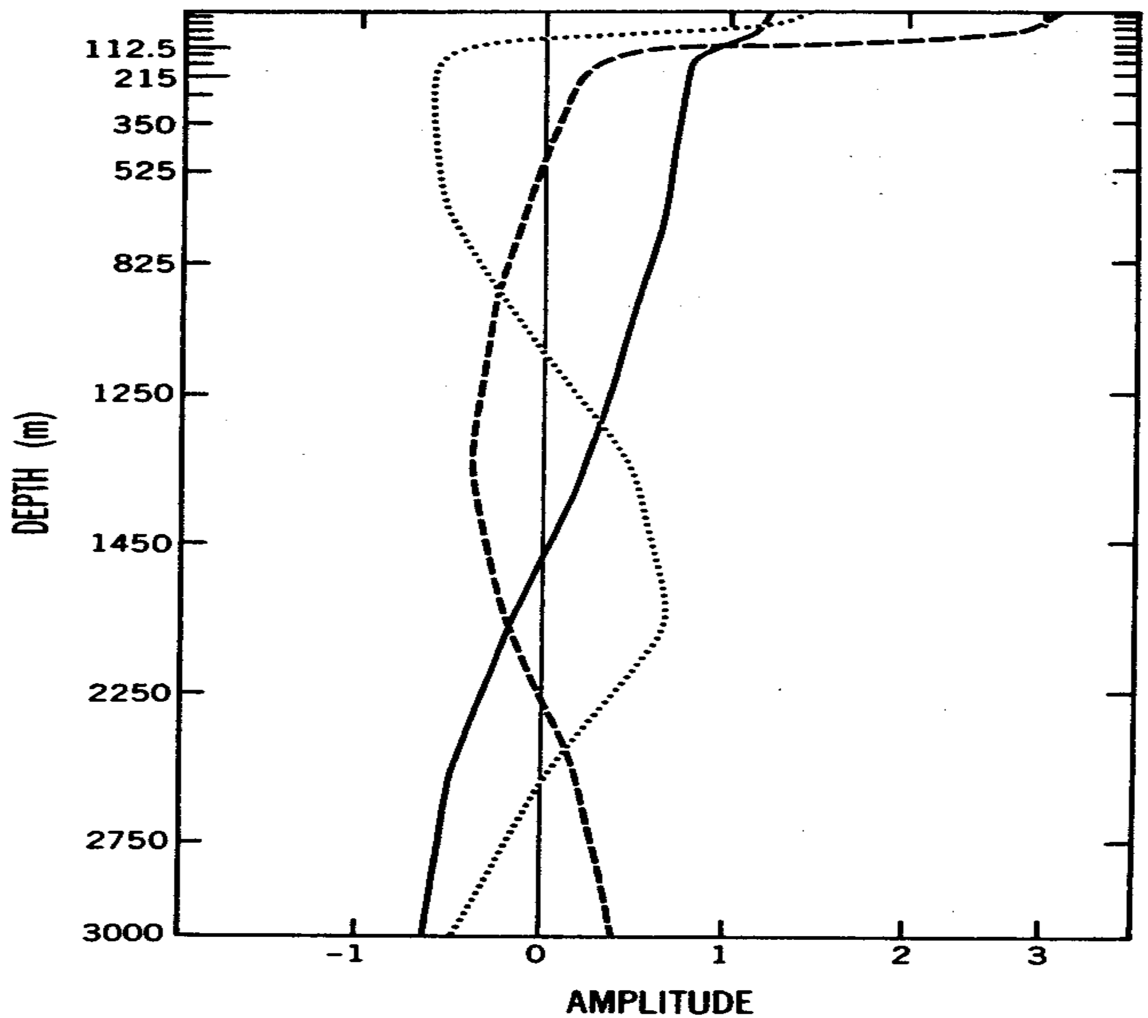
Upper Layer *u'* (cm/s, Blue)
Thermocline *u'* (cm/s, Black)
SST' (^{o}C * 12)
at 165^{o}E



Propagation of Second-Baroclinic Kelvin Waves and ECM



Typical temperature profile and Brunt-Vaisala Frequency at the Equatorial Pacific



Three gravest vertical modes for u’ calculated using a linear, continuously stratified, hydrostatic model with the Boussinesq approximation [after *Philander*, 1990]. Note that the node for the first baroclinic mode is at around 1500 m depth.

Equatorial Layered Model (McCreary and Yu, 1992)

- 2 ½ (or 1 ½) - Layer
  - The First Two Layers Active
  - The Third Layer Motionless
- Momentum Balance
- Heat Balance
- Entrainment/Detrainment Rate
- Wind Forcing
- 1^{o} X 1^{o} Resolution

$$(h_1\mathbf{v}_1)_t + \nabla\cdot(\mathbf{v}_1 h_1 \mathbf{v}_1) + f\mathbf{k}\times h_1\mathbf{v}_1 + h_1\langle\nabla p_1\rangle^z$$

$$= \boldsymbol{\tau} + w_e\mathbf{v}_2 + w_d\mathbf{v}_1 - \upsilon_4\nabla^4(h_1\mathbf{v}_1) - \gamma h_1 u_1\mathbf{i},$$

$$h_{1t} + \nabla\cdot(h_1\mathbf{v}_1) = w_e + w_d - \kappa_4\nabla^4 h_1,$$

$$T_{1t} + \mathbf{v}_1\cdot\nabla T_1 = Q_1/h_1 - w_e(T_1 - T_2)/h_1 - \kappa_4\nabla^4 T_1,$$

$$(h_2\mathbf{v}_2)_t + \nabla\cdot(\mathbf{v}_2 h_2 \mathbf{v}_2) + f\mathbf{k}\times h_2\mathbf{v}_2 + h_2\langle\nabla p_2\rangle^z$$

$$= -w_e\mathbf{v}_2 - w_d\mathbf{v}_1 - \upsilon_4\nabla^4(h_2\mathbf{v}_2) - \gamma h_2 u_2\mathbf{i},$$

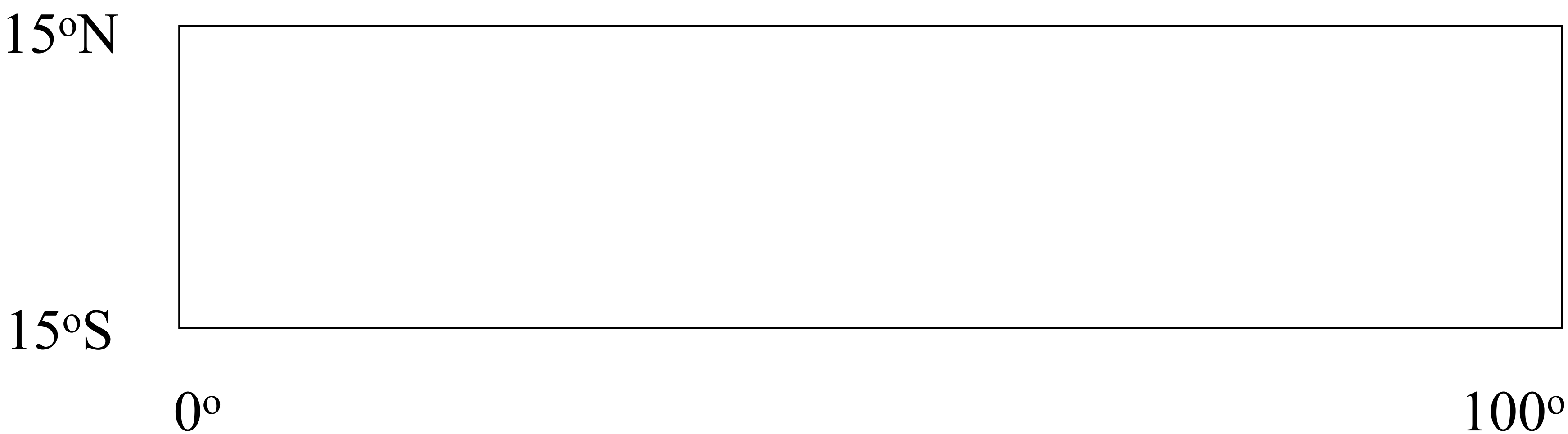
$$h_{2t} + \nabla\cdot(h_2\mathbf{v}_2) = -w_e - w_d - \kappa_4\nabla^4 h_2,$$

$$T_{2t} + \mathbf{v}_2\cdot\nabla T_2 = Q_2/h_2 - w_d(T_1 - T_2)/h_2 - \kappa_4\nabla^4 T_2.$$

Model Parameters (McCreary and Yu, 1992)

Biharmonic mixing coefficients	$\upsilon_4 = \kappa_4 = 2\times10^{21}\mathrm{cm}^4\mathrm{s}^{-1}$
Maximum value of damper	$\gamma = 1\ \mathrm{day}^{-1}$
Surface heating time scale	$t_1 = 100$ day
Lower-layer heating time scale	$t_2 = 500$ day
Entrainment time scale	$t_e = 1$ day
Detrainment time scale	$t_d = 50$ day
Entrainment depth	$H_e = 75\mathrm{m}$
Detrainment depth	$H_d = 75\mathrm{m}$
Coefficient of thermal expansion	$\alpha = 0.00025°\mathrm{C}^{-1}$
Characteristic speed of mode 1	$c_1 = 316\mathrm{cm\ s}^{-1}$
Characteristic speed of mode 2	$c_2 = 123\mathrm{cm\ s}^{-1}$

Model Area



Surface Winds
(Trade Winds)

$$\tau^x = \tau_o X(x) Y(y) T(t),$$

$$\tau_o = -0.5 \text{dyn cm}^{-2}.$$

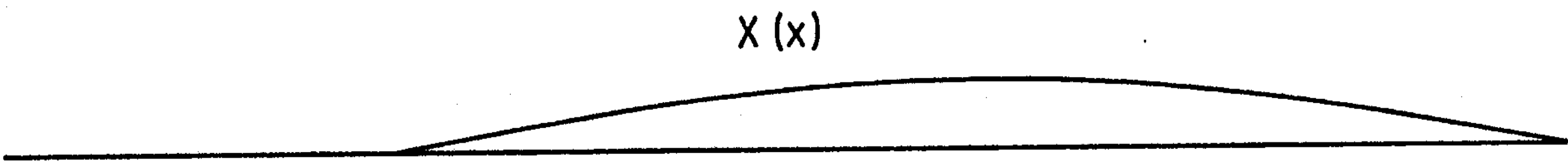
Y(y)=1 (No Latitudinal Variance).

T(t) = Ramp function that increases linearly from 0 to 1 in the first 5 days

Zonal Variation of the Trade Winds

$$X(x) = \cos[\pi(x - \bar{x})/L]\theta[(x - \bar{x})^2 - L^2/4],$$

$$\bar{x} = 62.5° \text{ and } L = 75°.$$



Initial Conditions

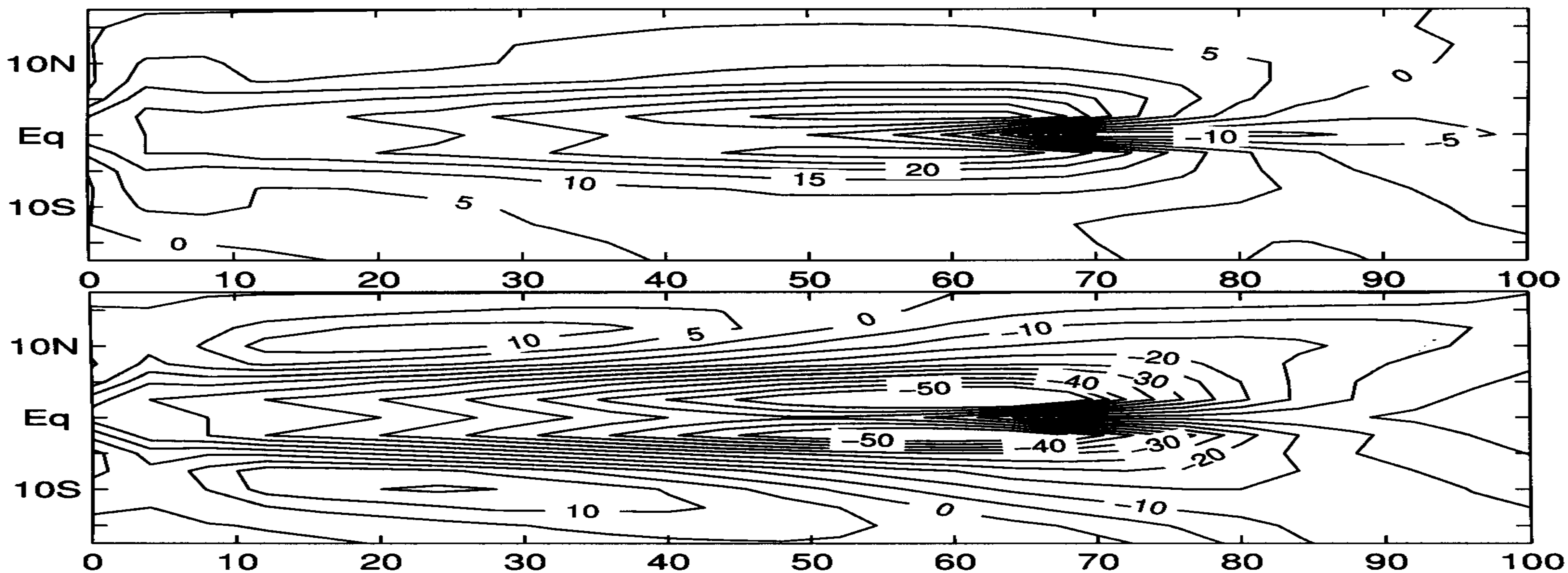
Initial thickness of upper layer	$H_1 = 75\text{m}$
Initial thickness of lower layer	$H_2 = 175\text{m}$
Initial temperature of upper layer	$T_1^* = 28°\text{C}$
Initial temperature of lower layer	$T_2^* = 15°\text{C}$
Temperature of deep ocean	$T_3 = 0°\text{C}$

Model Integration

- (1) Model is integrated for 1080 days to reach nearly equilibrium state.
- (2) Westerly wind patch is added at day-1080 for 25 days, and then is removed.
- (3) Model is integrated for 1000 days.

Control Run

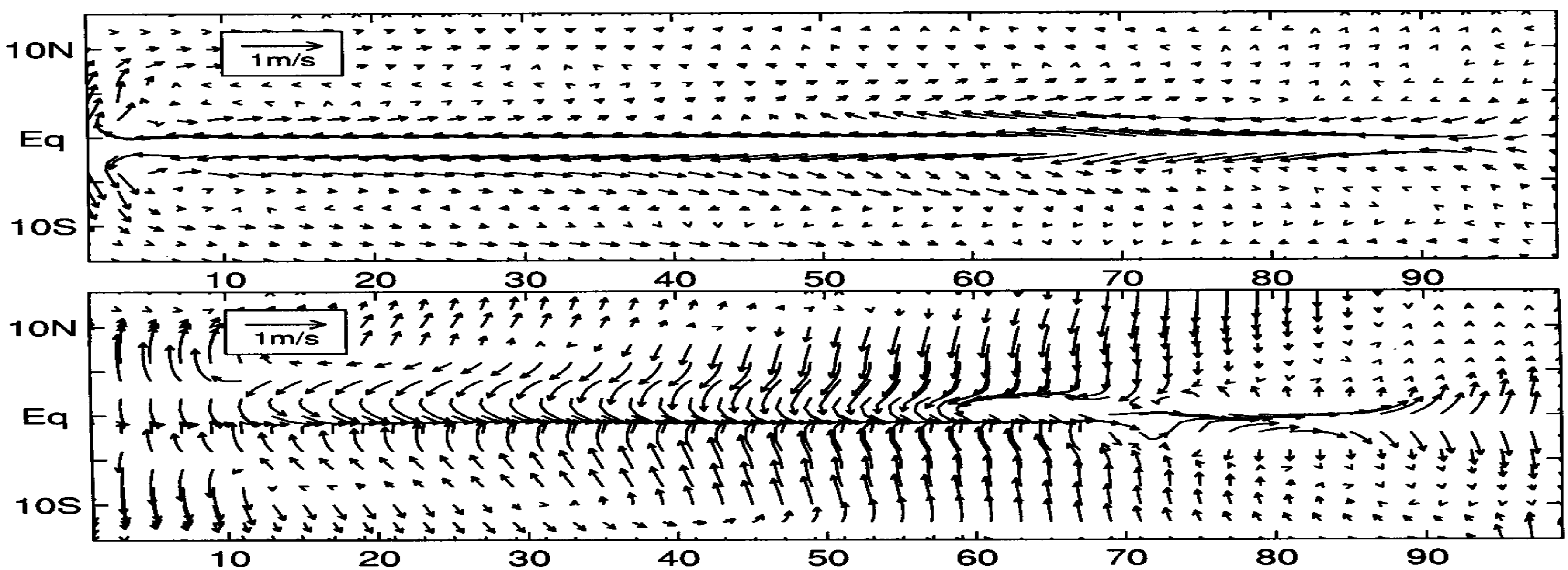
Layer Thickness Anomaly (m) at Day-1080:
(a) 1st Layer, (b) 2nd Layer.



Control Run

Horizontal Currents at Day-1080.

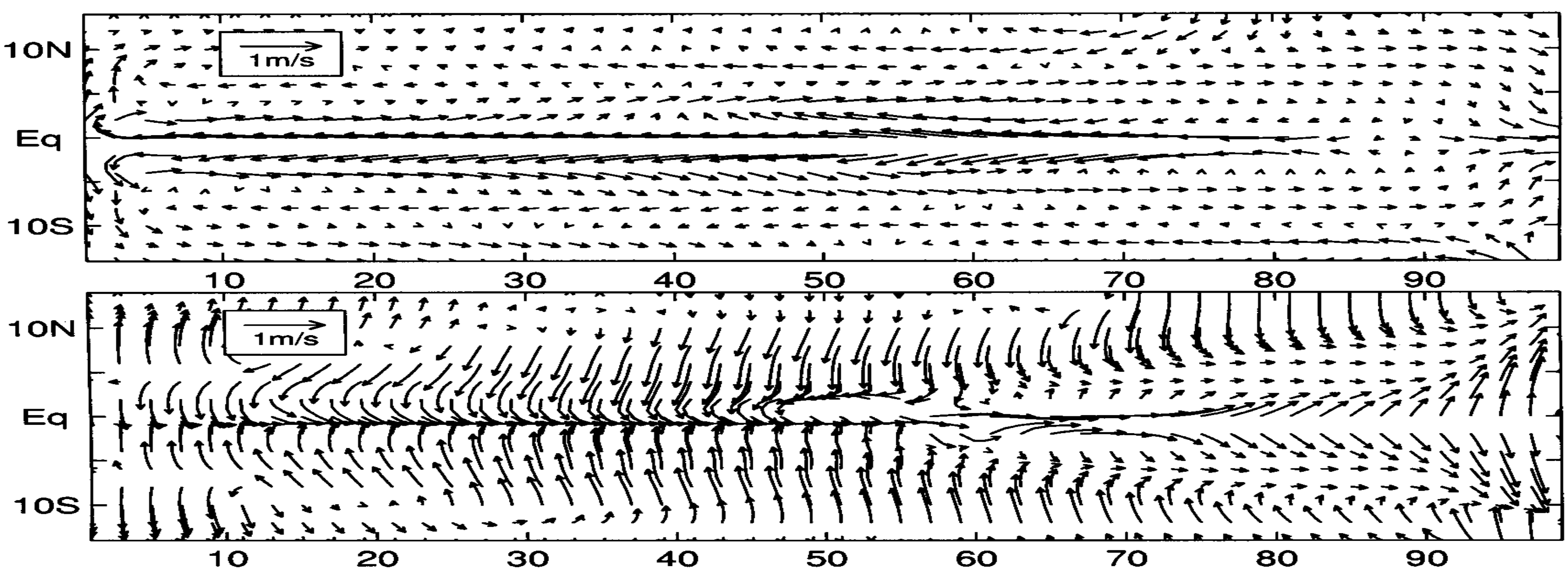
(a) 1st Layer: SEC; 2nd Layer: EUC



Westward Shift of the Trade Wind Maximum

$X = 53^o$

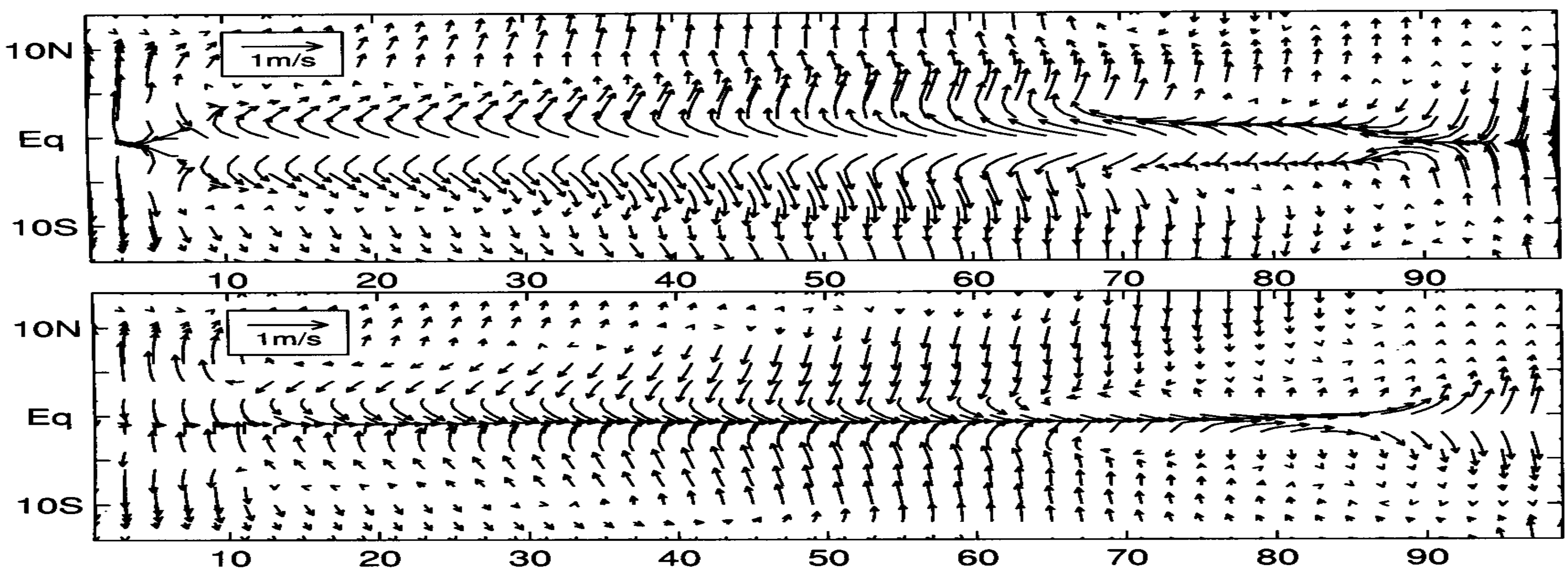
Westward Shift of Maximum Currents



Trade Winds Reduced to 85%

(a) SEC weakens

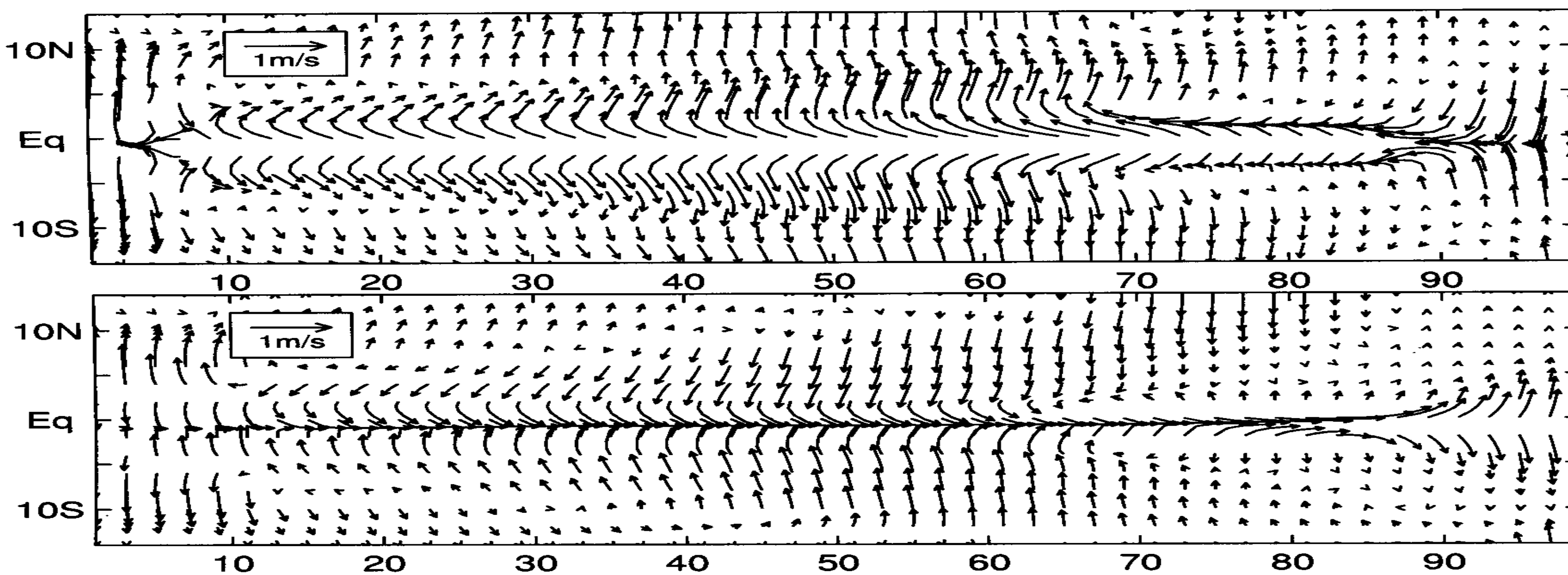
(b) EUC weakens



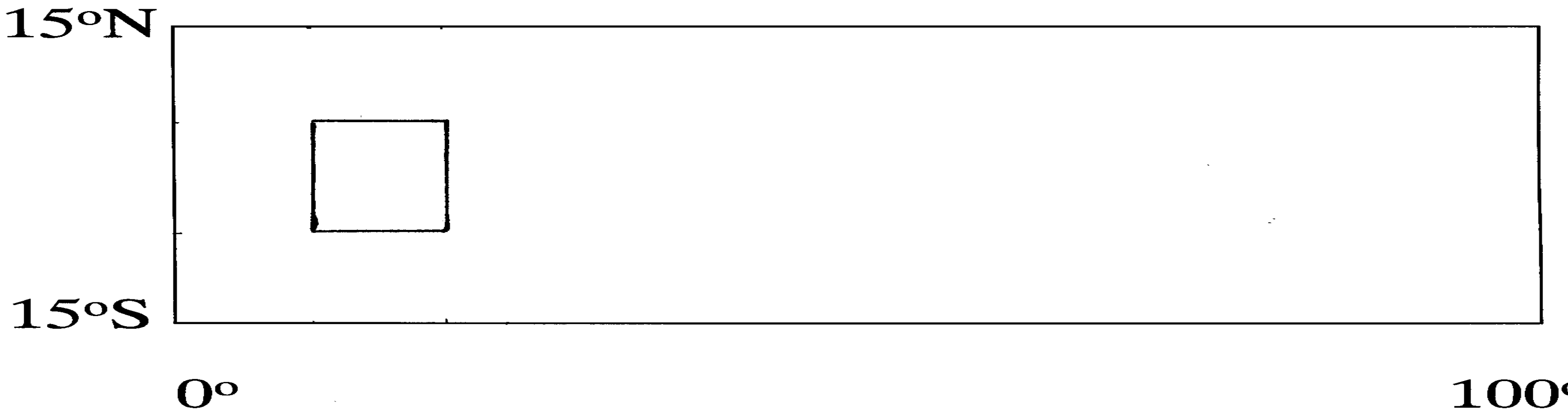
Trade Winds Reduced to 70%

(a) SEC weakens

(b) EUC weakens



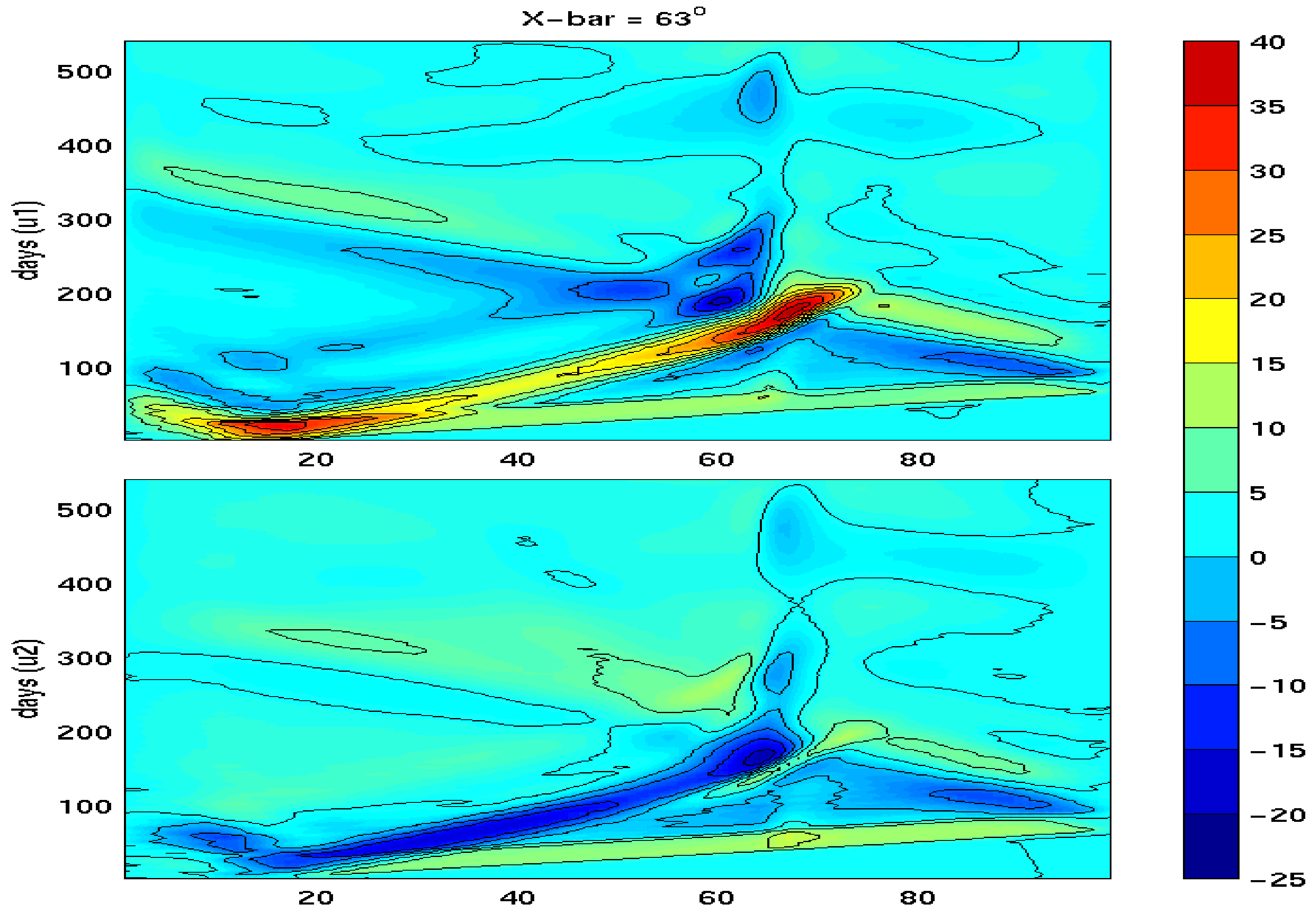
Westerly Wind Burst Patch



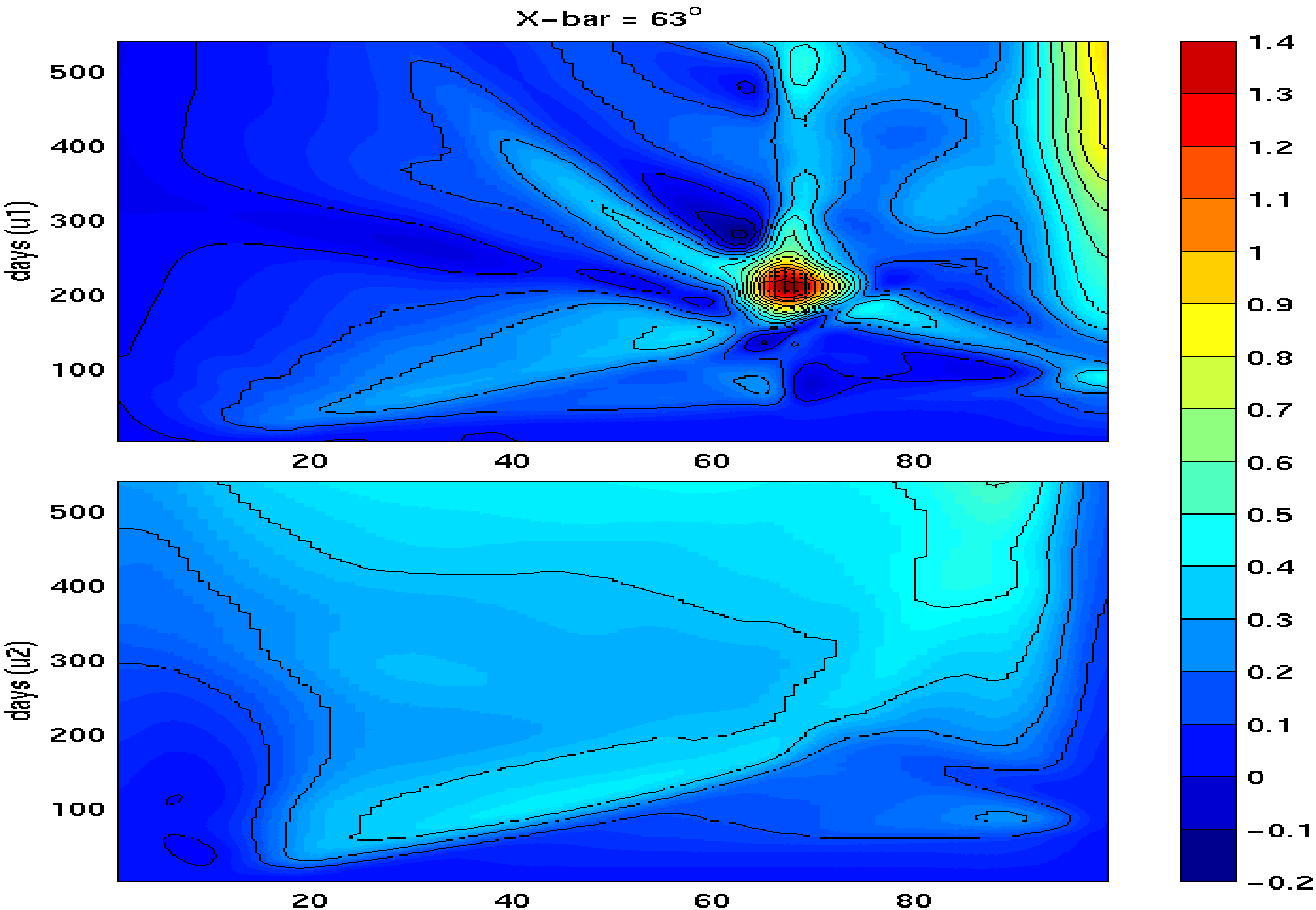
Westerly wind = 10 m/s

Westerly wind patch is added at day-1080 for 25 days, and then is removed.

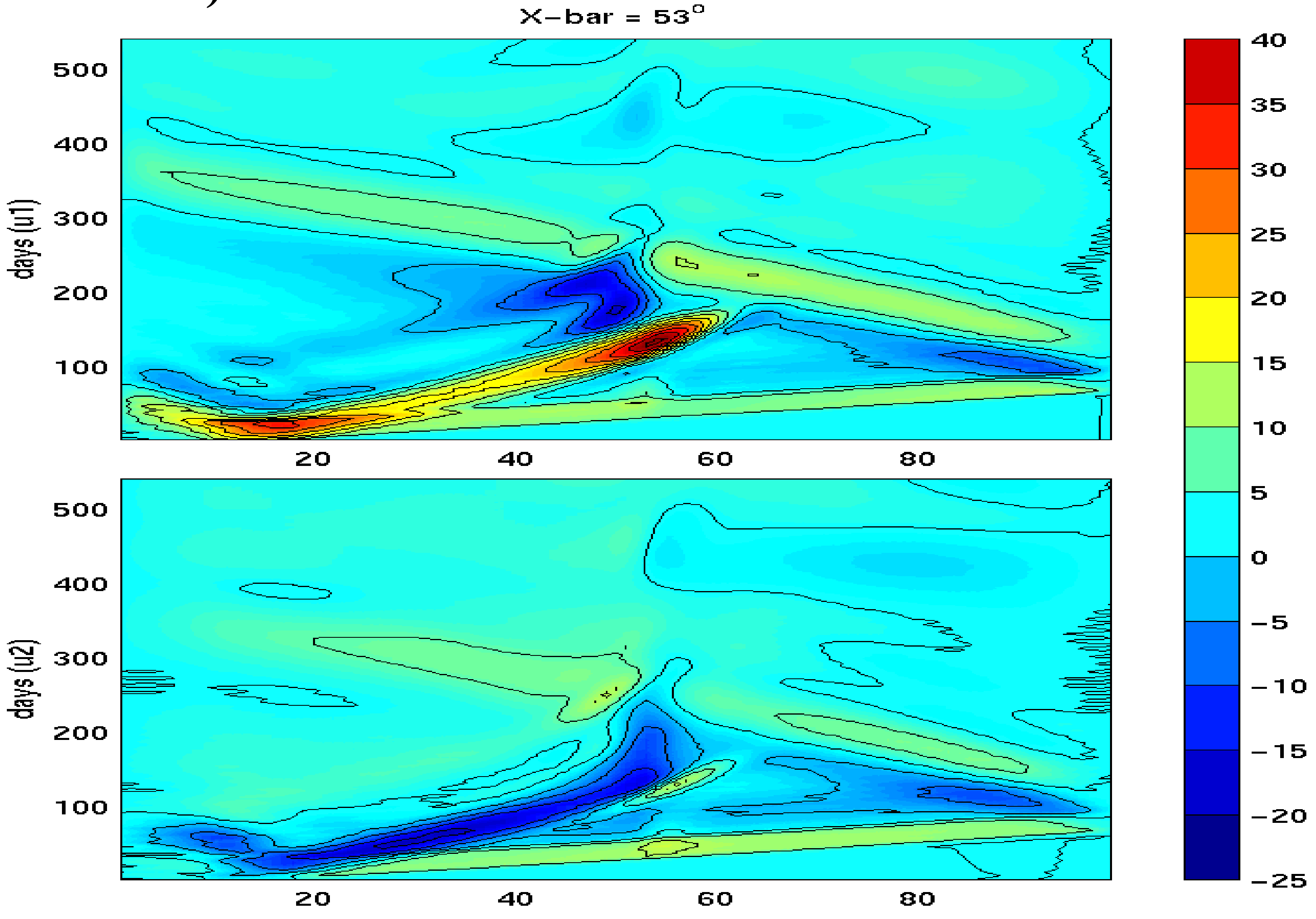
Time-Longitude Cross Section of Zonal Velocity Anomaly (cm/s) : (a) 1st Layer, (b) 2nd Layer (Control Run)



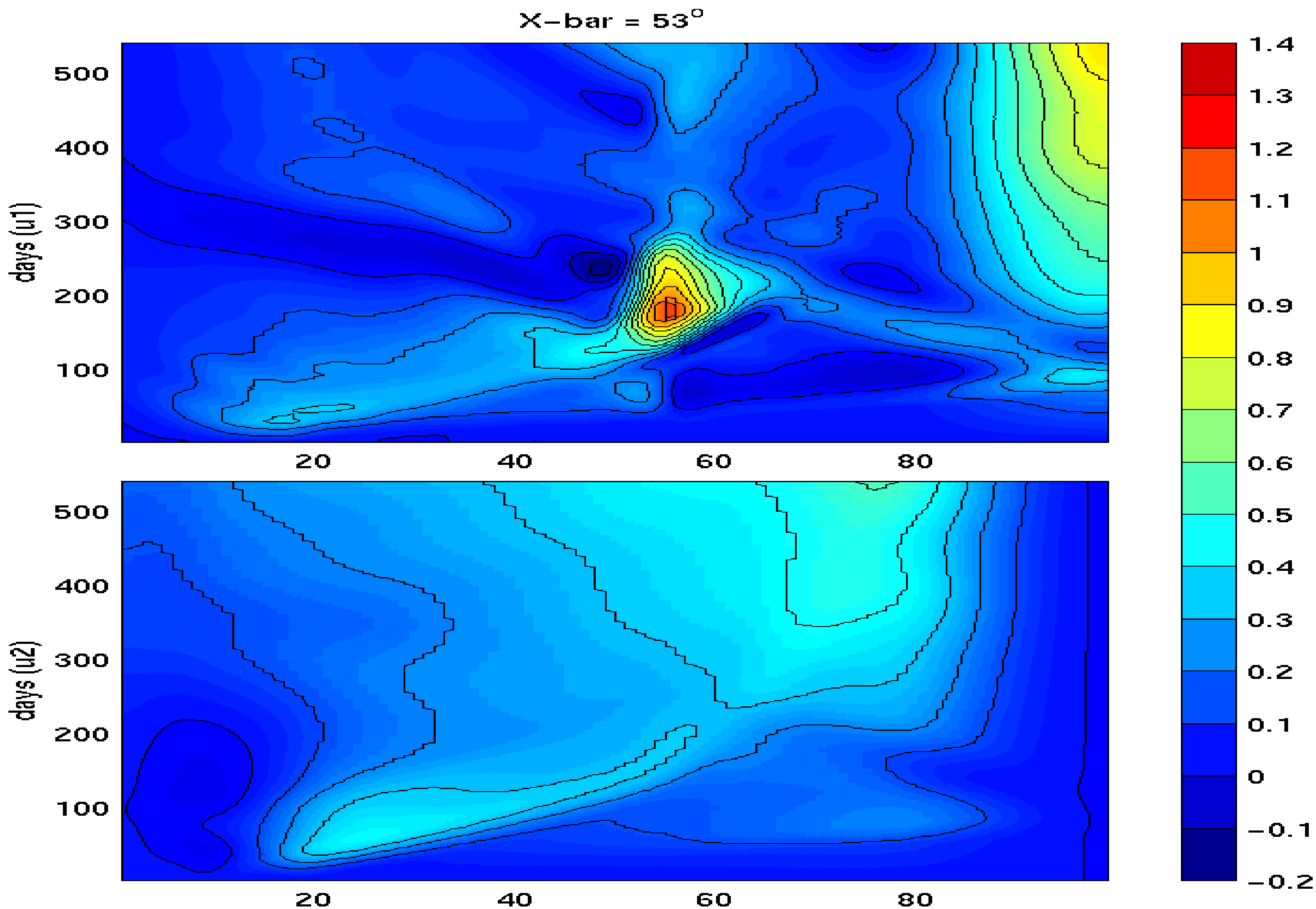
Time-Longitude Cross Section of Temperature Anomaly (^{o}C) : (a) 1st Layer, (b) 2nd Layer (Control Run)



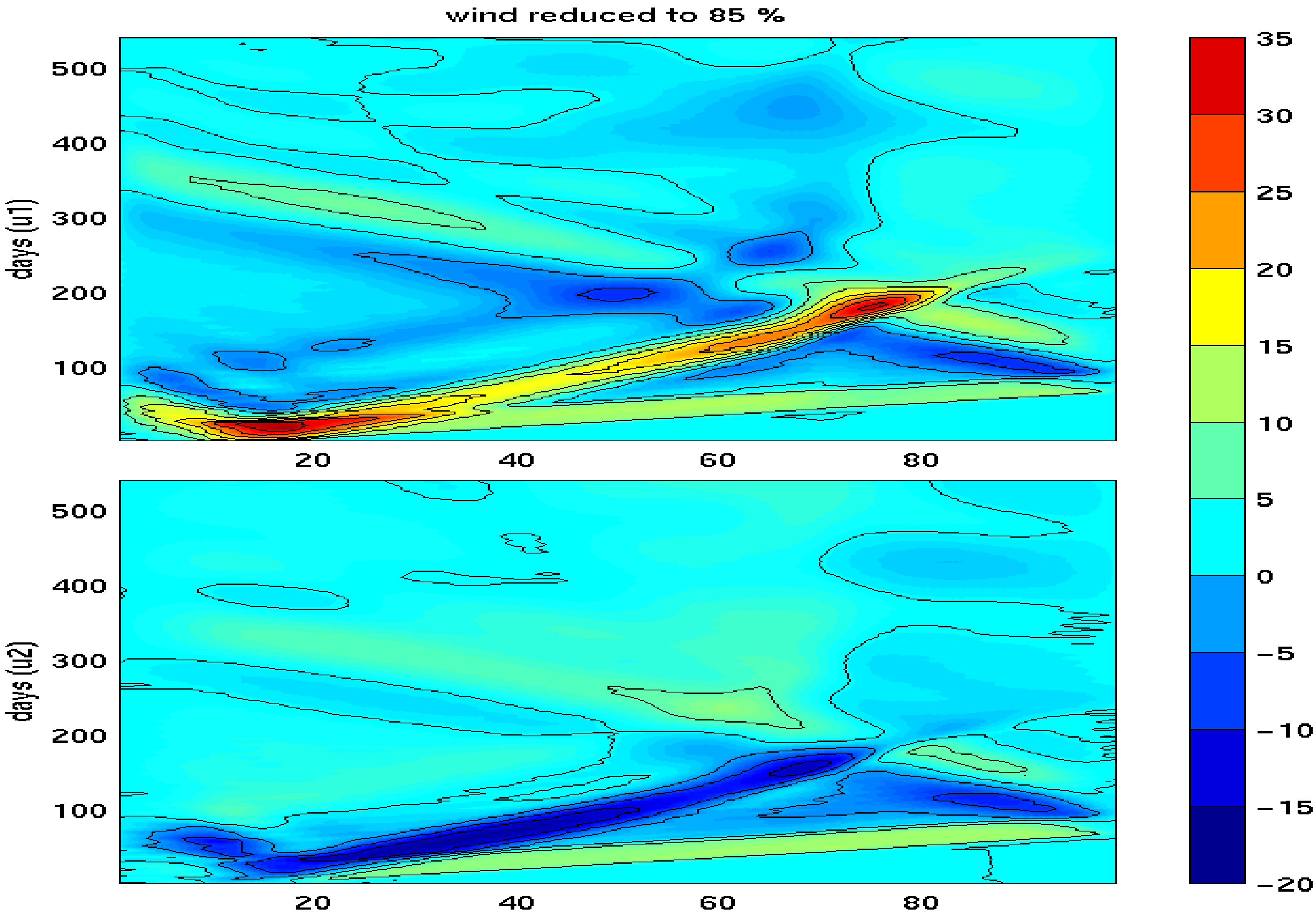
Time-Longitude Cross Section of Zonal Velocity Anomaly (cm/s) : (a) 1st Layer, (b) 2nd Layer (Trade Wind Maximum Shifted Westward)



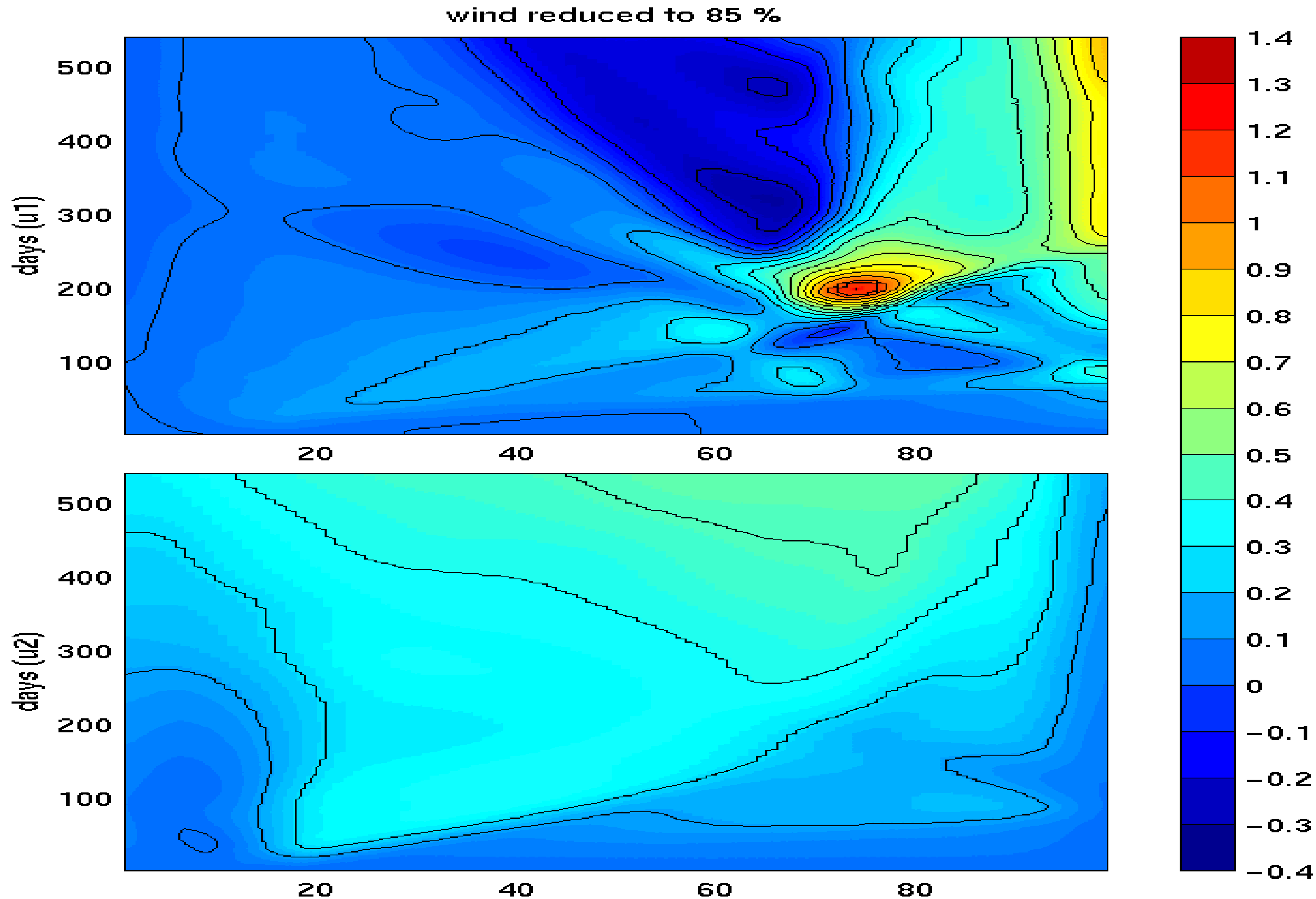
Time-Longitude Cross Section of Temperature Anomaly (^oC) : (a) 1st Layer, (b) 2nd Layer (Trade Wind Maximum Shifted Westward)



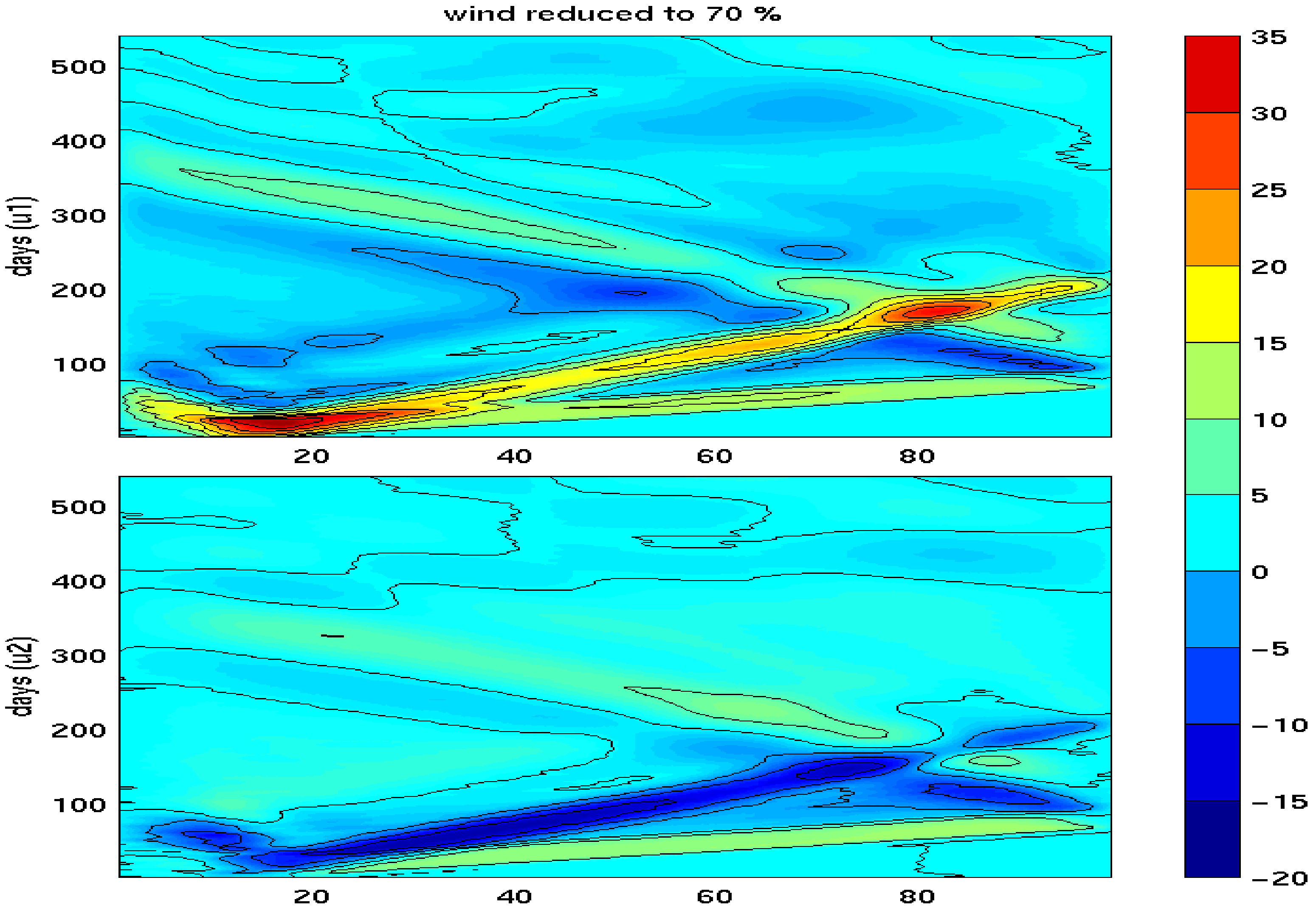
Time-Longitude Cross Section of Zonal Velocity Anomaly (cm/s) : (a) 1st Layer, (b) 2nd Layer (Trade Winds Reduced to 85%)



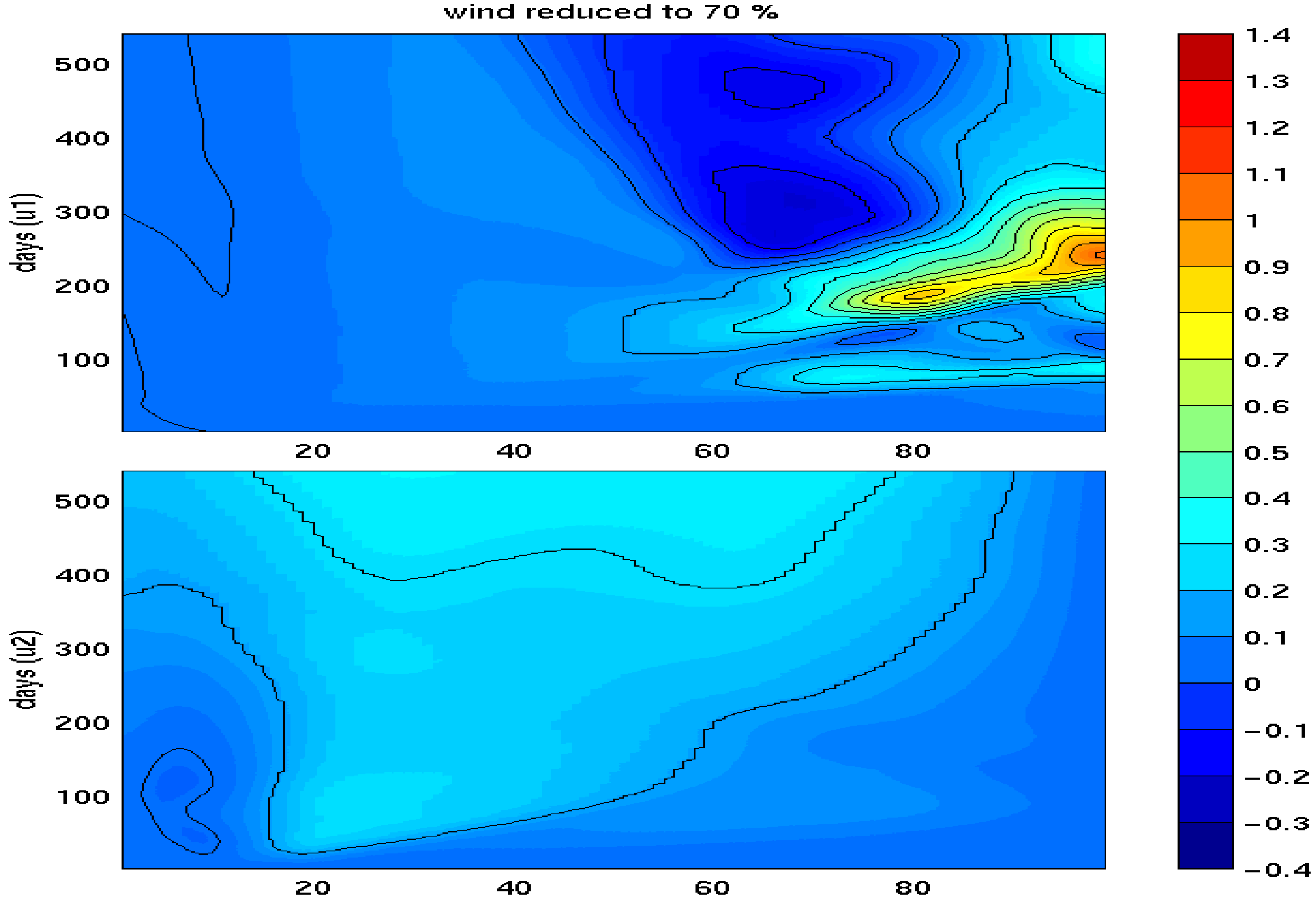
Time-Longitude Cross Section of Temperature Anomaly (^oC) : (a) 1st Layer, (b) 2nd Layer (Trade Winds Reduced to 85%)



Time-Longitude Cross Section of Zonal Velocity Anomaly (cm/s) : (a) 1st Layer, (b) 2nd Layer (Trade Winds Reduced to 70%)



Time-Longitude Cross Section of Temperature Anomaly (^oC) : (a) 1st Layer, (b) 2nd Layer (Trade Winds Reduced to 70%)



Conclusions

- ECM weakens the surface cold advection that may lead to central Pacific warming
- Second baroclinic Kelvin waves cause ECM.
- Two-stage air-sea interaction mechanism is proposed for the El Nino onset.

Two-Stage Air-Sea Interaction Mechanism